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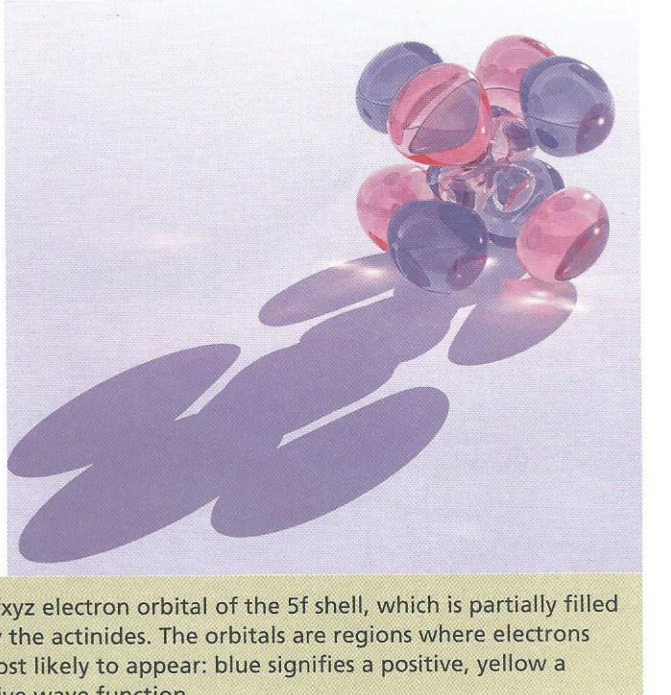
QUANTUM CHEMISTRY focuses on the application of wave functions to electrons in atomic or molecular orbitals. The first successful applications of wave mechanics to a molecule occurred in the late 1920s in the work of the German physicists Walter Heitler, Fritz London, and Friedrich Hund. The first successful applications to a distinctively chemical molecule with spatially directed chemical valences was the work of the Americans Linus Pauling and John Slater in 1931.

Niels Bohr had used the quantum hypothesis in 1913 to explain the stability of the electron's orbit about a positively charged nucleus. The connection that Bohr worked out in 1913 between the periodicity of electron-shell configurations in the atom and the periodicity of properties for chemical elements in the periodic table was improved in a famous paper of 1922. Bohr worked out—but did not calculate—a neat correlation of electron levels containing 2, 8, up to 18, and up to 32 electrons in the so-called K, L, M, and N shells with chemical periodic groups containing 2, 8, 8, 18, 18, and 32 elements. By this time Bohr and others were making use of Niels Bjerrum's formulation of a quantum theory for molecules (1911–1914) that quantified a classical model of a vibrating rotator.

Werner Heisenberg's formulation of resonance in wave functions (1926) suggested a breakthrough for chemists in the long-standing puzzle of how two electrical particles of like charge can unite to form a stable covalent chemical bond. In 1927, Heitler and London successfully applied Heisenberg's resonance formulation of electron wave functions to the two-atom, two-electron hydrogen molecule. At the same time Hund published a different treatment generalizing the work of the Danish physicist Oyvind Burrau on the hydrogen molecule ion, which produced reliable energy values using elliptical coordinates for the electron in orbit around two protons. Hund assumed that each electron moves in a potential field that results from all the nuclei and from other electrons present in the molecule. The Heitler-London approach became known as the atomic orbital method (AO) and the Hund approach as the molecular orbital method (MO).



The 5fxyz electron orbital of the 5f shell, which is partially filled out by the actinides. The orbitals are regions where electrons are most likely to appear: blue signifies a positive, yellow a negative wave function.

Independently, Slater and Pauling developed ways to explain directed chemical valence by proposing the mixing of the s (spherical) and p (elliptical) energy levels of the four valence electrons in the carbon atom. The mixing, or hybridization, creates wave functions of equal energy with electron distributions oriented toward the corners of a tetrahedron. Pauling and Slater demonstrated that deviation from a 90-degree bond angle could be taken as evidence of mixing, or hybridization, of the electron orbitals.

During 1931–1935, Robert Mulliken used Hund's approach and Douglas Rayner Hartree's group-theoretical methods to develop molecular orbital theory, as did Erich Hückel and Bernhard Eistert in Germany. While Pauling's atomic orbital method prevailed in the United States in the next decade, in England, John Edward Lennard-Jones, Hugh Christopher Longuet-Higgins, and Charles Alfred Coulson took up the molecular orbital method with its greater potential for mathematical application and development. Coulson successfully demonstrated in 1939 how electrons in benzene move over the whole molecule instead of being restricted to the region between two particular atoms. With the development of high-speed digital computers after the war, the more mathematically difficult MO method came to be preferred by most theoretical chemists despite Pauling's argument that the AO method was more natural to the chemist and its rougher approximations often did the job. Among proponents of MO theory, Coulson persuaded many chemists (although not Pauling) that MO methods complemented AO methods and offered considerably greater capability for solving chemical problems. Coulson's influential textbook *Valence* appeared in 1952.

The development of orbital symmetry rules by Robert Simpson Woodward and Roald Hoffmann in the 1960s, which allowed highly specific predictions of stereochemical details and reaction outcomes, assisted the switch to the MO method. Building on the work of Coulson and Longuet-Higgins, the Kyoto chemist Ken'ichi Fukui developed the frontier orbital theory of reactions (1950) that showed how the progress of reactions depends upon the geometry and relative energies of the highest recipient molecular orbital of one reactant and the lowest molecular orbital of the other.

MARY JO NYE

QUANTUM ELECTRODYNAMICS (QED) is the quantum field theory describing the interaction of charged particles with photons. It represents positive and negative electrons by a quantized field satisfying the Dirac equation in the presence of an electromagnetic (e.m.) field; charged spin 0 particles, such as pi mesons, by quantized field operators satisfying the Klein-Gordon equation; and the electromagnetic field by quantized field operators satisfying Maxwell's equations. The source terms in these Maxwell equations are the charge-currents arising from the matter field in the presence of the quantized e.m. field. The small dimension-less constant $\alpha = 2\pi e^2/hc = 1/137$, where e is the electronic charge, h Planck's constant, and c the velocity of light, measures the coupling between the charged matter field and the electromagnetic field. Since α is so small, the coupled equations are usually solved "peturbatively," that is, as a power series expansion in α. This perturbative approach has had amazing success in calculating extremely fine details in atomic spectra, accounting for the electromagnetic properties of electrons and muons, and predicting with precision the outcome of collisions between high-energy positive and negative electrons. As Toichiro Kinoshita and Donald Yennie, two theorists who have carried out some of the most extensive and difficult calculations testing the limits of QED, wrote in 1990, "it is inconceivable that any theory which is conceptually less sophisticated could produce the same results."

Richard Feynman's great contribution to QED was a technique by which perturbations could be visualized and calculated by straightforward diagrams. The diagrams indicate both why and how certain processes take place in particular systems. In Feynman's approach, as generalized by Freeman Dyson, each quantized field (and associated particle) is characterized by a "propagator" represented in a Feynman diagram by a line, which if internal connects to two vertices, and if external, that is, if corresponding to an incoming or outgoing particle, connects to a single vertex. Each interaction is represented by a vertex characterized by a coupling constant and a factor describing the interaction between the fields. For a given process, relatively simple expressions occur in the lowest order of perturbation theory. The diagrams that correspond to higher order contributions contain closed loops and entail integrations over the momenta of the propagators involved in the loops. In almost all cases these integrals diverge because of contributions from large momenta.

The anomalous magnetic moment of a (quasi-free) electron means the deviation from the value predicted by the Dirac equation. According to Dirac's theory, the electron has an intrinsic magnetic moment accompanying its spin, the value of which when expressed in the form $g_e = eh/4\pi mc$ is given by $g_e = 2$. The electron's anomalous magnetic moment is defined as $a_e = (g_e - 2)/2$.

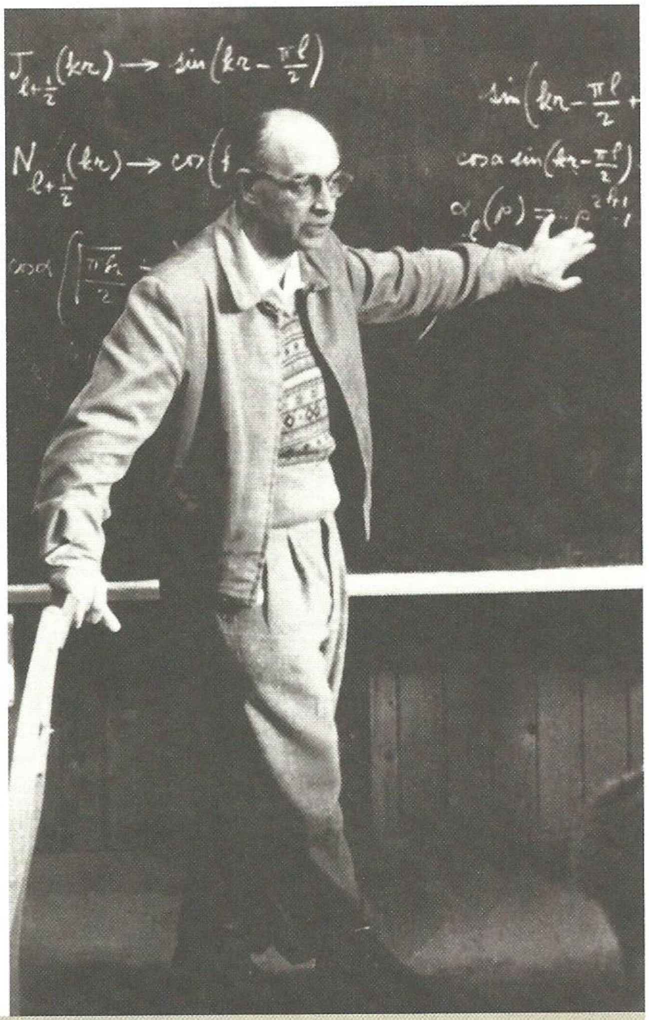
Julian Schwinger's computation of a_e in 1947 constituted a landmark in the postwar developments of QED. It confirmed the experimental value that had been obtained by Isador Isaac Rabi and his associates and also the ideas of mass and charge renormalization in the low orders of QED. Since that time, both the experiments and the theory have been improved by several orders of magnitude and have provided the most precise and rigorous tests for the validity of QED. To date, the best theoretical and experimental values of the anomalous magnetic moment of the electron agree to ten significant figures—(in units of $eh/4\pi mc$) 1.001 159 652 17 (theoretical) against 1.001 159 652 19 (measured).

Silvan S. Schweber

QUANTUM FIELD THEORY. When initially formulated, quantum mechanics described non-relativistic systems with a finite number of degrees of freedom. The extension of the formalism to include the interaction of charged particles with the electromagnetic field-treated quantum mechanically brought out the difficulties connected with the quantization of systems with an infinite number of degrees of freedom. The effort to make the quantum theory conform with special relativity disclosed further difficulties. To address both sets of problems, Ernst Pascual Jordan, Oskar Klein, Eugene Wigner, Werner Heisenberg, Wolfgang Pauli, Enrico Fermi, and others developed quantum field theory (QFT) during the late 1920s. P. A. M. Dirac had taken the initial step in 1927 with a quantum mechanical description of the interaction of charged particles with the electromagnetic field, which he described as an (infinite) assembly of photons, that is, of massless spin 1 particles. Dirac considered "particles" (whether they had a rest mass or, like photons, had none) to be the "fundamental" substance. In contrast, Jordan insisted that fields constituted the "fundamental" substance.

The history of theoretical elementary particle physics until the mid-1970s can be narrated in terms of oscillations between the particle and field viewpoints epitomized by Dirac and by Jordan. QFT proved richer in potentialities and possibilities than the quantized-particle approach. By the mid-1930s, the imposition of special relativity on QFT had produced genuinely novel features: the possibility of particle creation and annihilation, as first encountered in the quantum mechanical description of the emission and absorption of photons by charged

Richard Feynman (1918–1988), on the right, and Paul Dirac (1902–1984), perhaps discussing quantum field theory



Italian-born American physicist Enrico Fermi (1901–1954)

particles; the existence of anti-particles; and the complexity of the "vacuum." The latter was now seen to be not a simple substance but the seat of fluctuations in the measured observables, which fluctuations are the larger the smaller the volume probed.

Fermi's theory of beta-decay (1933–1934) was the important landmark of field theoretic developments of the 1930s. It had been recognized since 1915 that the nucleus was the site of all radioactive processes, including β-radioactivity. The process of β-decay—in which a radioactive nucleus emits an electron (β-ray) and increases its electric charge from Z to $Z + 1$—had been studied extensively during the first decade of the century. In 1914, James Chadwick found that the energy of the emitted electrons varied continuously up to some maximum at which conservation held to the accuracy of the measurements in the experiment. By the end of the 1920s, no satisfactory explanation of the continuous β-spectrum had been found and some physicists, in particular Niels Bohr, proposed giving up energy conservation in β-decay processes. In December 1930, Pauli, in a letter addressed to the participants of a conference on radioactivity, countered with "a desperate remedy." He suggested that "there could exist in the nuclei electrically neutral particles that I wish to call neutrons [later renamed neutrinos by Fermi], which have spin 1/2 .... The continuous β-spectrum would then become understandable by the assumption that in β-decay a [neutrino] is emitted together with the electron, in such a way that the sum of the energies of the [neutrino] and electron is constant."

Fermi took Pauli's hypothesis seriously when he heard about it for the first time at the Solvay Congress of 1933. Fermi soon formulated a theory of β-decay that marked a change in the concept of "elementary" processes. Fermi supposed that electrons do not exist in nuclei before their emission, but that (to quote his version of 1934) "they, so to say, acquire their existence at the very moment when they are emitted; in the same manner as a quantum of light, emitted by an atom in a quantum jump, can in no way be considered as pre-existing in the atom prior to the emission process. In this theory, then, the total number of the electrons and of the neutrinos (like the total number of light quanta in the theory of radiation) will not necessarily be constant, since there might be processes of creation or destruction of these light particles."

Both Fermi's theory of β-decay and quantum electrodynamics (QED) made clear the power of a quantum field theoretical description. In particular, they indicated that the electromagnetic forces between charged particles could be understood as arising from the exchange of virtual photons between the particles—virtual particles because they do not obey the energy-momentum relation that holds for free photons. When one of the charged particle emits a (virtual) photon of momentum k, it changes its momentum by this amount. When the second charged particle absorbs this virtual photon, it changes its momentum by k. This exchange is the mechanism of the force between the interacting particles. The range of the force generated is inversely proportional to the mass of the virtual quantum exchanged. Zero-mass photons generate electromagnetic forces of infinite range. Spin-zero quanta of mass m generate forces with a range of the order h/mc. This insight led Hideki Yukawa to postulate that the short-range nuclear forces between nucleons could arise from the exchange of massive spin 0 bosons. Another important lesson learned from QED and Fermi's theory of β-decay was the protean nature of particles. When interacting with one another "particles" can metamorphose their character and number: in a collision between an electron and its anti-particle, the positron, the electron and positron can annihilate and give rise to a number of photons.

By the late 1930s, physicists understood the formalism of quantum field theory and its difficulties. All relativistic QFTs have the mathematical problem that the calculations of the interactions between particles give infinite, that is, nonsensical results. The root cause—fields definable at a point in space-time of these divergences was the assumption of locality, the assumption that the local fields—fields definable at a point in space-time point—whose quanta are the experimentally observed particles interact locally, i.e. at a point in space time.

Local interaction terms implied that in QED photons will couple with (virtual) electron-positron pairs of arbitrarily high momenta, and that electrons and positrons will couple with (virtual) photons of arbitrary high momenta, in both cases giving rise to divergences. The problem impeded progress throughout the 1930s and caused most of the workers in the field to doubt the correctness of QFT. The many proposals to overcome these divergences advanced during the 1930s all ended in failure. The pessimism of the leaders of the discipline—Bohr, Pauli, Heisenberg, Dirac, and J. Robert Oppenheimer—was partly responsible for the lack of progress. They had witnessed the overthrow of the classical concepts of space-time and had themselves rejected the classical concept of determinism in the description of atomic phenomena. They had brought about the quantum mechanical revolution. They were convinced that only further conceptual revolutions would solve the divergence problem in quantum field theory.

The way to circumvent the difficulties was indicated by Hendrik Kramers in the late 1930s, and his suggestions were implemented after World War II. These important developments stemmed from the attempt to explain quantitatively the discrepancies between the empirical data and the predictions of the relativistic Dirac equation for the level structure of the hydrogen atom and the value it ascribed to the magnetic moment of the electron. These deviations had been observed in reliable and precise molecular beam experiments carried out by Willis Eugene Lamb, Jr., and by Isidor Isaac Rabi and coworkers at Columbia, and were reported at the Shelter Island Conference in the fall of 1947. Shortly after the conference, Hans Albrecht Bethe showed that the Lamb shift (the deviation of the $2s$ and $2p$ levels of hydrogen from the values given by the Dirac equation) was of quantum electrodynamical origin, and that the effect could be computed by making use of what became known as "mass renormalization," the idea that had been put forward by Hendrik Kramers.

The parameters for the mass m_0 and for the charge e_0 that appear in the equations defining QED are not the observed charge and mass of an electron. The observed mass m enters the theory through the requirement that the energy of the physical state corresponding to an electron moving with momentum p be equal to $(p^2 + m^2)^{1/2}$. The observed charge e enters through the requirement that the force between two electrons at rest separated by a large distance r satisfy Coulomb's law e^2/r^2. Julian Schwinger and Richard Feynman showed that the divergences encountered in the low orders of perturbation theoretic calculations could be eliminated by re-expressing the parameters m_0 and e_0 in terms of the observed values m and e, a procedure that became known as mass and charge renormalization. In 1948, Freeman Dyson working at the Institute for Advanced Study in Princeton proved that these renormalizations could absorb all the divergences arising in scattering processes (the *S*-matrix) in QED to all orders of perturbation theory. More generally, Dyson demonstrated that only for certain kinds of quantum field theories can all the infinities be removed by a redefinition of a finite number of parameters. He called such theories renormalizable. Renormalizability thereafter became a criterion for theory selection.

The idea of mass and charge renormalization, implemented through a judicious exploitation of the symmetry properties of QED, made it possible to formulate and to give physical justifications for algorithmic rules to eliminate all the ultraviolet divergences that had plagued the theory and to secure unique finite answers. The success of renormalized QED in accounting for the Lamb shift, the anomalous magnetic moment of the electron and of the muon, the scattering of light by light, the radiative corrections to the scattering of photons by electrons, and the radiative corrections to pair production was spectacular.

Perhaps the most important theoretical accomplishment between 1947 and 1952 was providing a firm foundation for believing that local quantum field theory was the framework best suited for the unification of quantum theory and special relativity. Perspicacious theorists, like Murray Gell-Mann also noted the ease with which symmetries—both space-time and internal symmetries—could be incorporated into the framework of local quantum field theory. Gauge invariance became a central feature of the quantum field theoretical description of the electromagnetic field. Subsequently, the weak and the strong forces were similarly described in terms of gauge theories.

SILVAN S. SCHWEBER

QUANTUM PHYSICS. The proximate origin of the quantum theory was a perplexing paper published by Max Planck in 1900. In it he showed that the formula he had proposed for the empirically determined spectral density of blackbody radiation could be derived by setting the energy of the collection of charged harmonic "resonators" (which he used to represent atoms capable of emitting and absorbing electromagnetic radiation) of frequency ν equal to an integral multiple of $h\nu$. Here h stood for a new physical constant necessary to fit the empirical spectrum and ν for the frequency of the resonator. The derivation required recourse to Ludwig Boltzmann's probability calculation for the entropy of a gas. It appears that, in adapting it to the blackbody problem, Planck did not recognize that he had made a break with the physics he had used to describe radiation.

In any case, Planck had full confidence in the representation of the electromagnetic field given by James Clerk Maxwell and Hendrik Antoon Lorentz. The unification of light with electromagnetism, the demonstration of the "reality" of electromagnetic waves by Heinrich Hertz, and the description given by the Maxwell-Lorentz equations of a multitude of wave phenomena was for Planck, and for almost all of his contemporaries, convincing evidence of the continuous nature of radiation. Albert Einstein entertained doubts. Having scrutinized the statistical mechanical foundations upon which Planck based his derivation of his formula for the spectral density of blackbody, Einstein concluded in 1905 that a few phenomena, like the photoelectric effect, could be explained easily if "the energy of monochromatic light consists of a finite number of energy quanta of magnitude $h\nu$, localized at various points of space [that] can be produced or absorbed only as units." At about the same time, Einstein realized that Planck's radiation theory required a radical discontinuity in the energy content of the individual resonators; with his "heuristic hypothesis" concerning the photo-effect, Einstein extended the discontinuity to the free electromagnetic field and to the interaction between light and matter.

Einstein's explanation in 1907 of the observed deviation at low temperature of the specific heat of simple solids from their classical value of $3Nk$ ($N =$ the number of molecules in a gram, $k =$ "Boltzmann's constant," a second universal constant from the blackbody formula) corroborated the quantum hypothesis. In Einstein's model of a solid, the potential that an atom experiences near its equilibrium position is the same for all the atoms of the solid. Hence for small vibrations near their equilibrium point all the atoms oscillate with the same frequency ν. Quantization implies that each oscillator can only have an energy equal to $E = nh\nu$, and Planck's formula gives, in the limit where $h\nu$ is small in comparison with kT ($T =$ temperature), the specific heat $3Nk$. At low enough temperatures, where the limit does not hold, characteristic deviations from the classical value occur, which Walther Nernst and others detected around 1910.

In his doctoral thesis on the electron theory of metals (1911), Niels Bohr concluded that atoms constructed according to the principles of classical physics could not represent the magnetic properties of metals. Working in Ernest

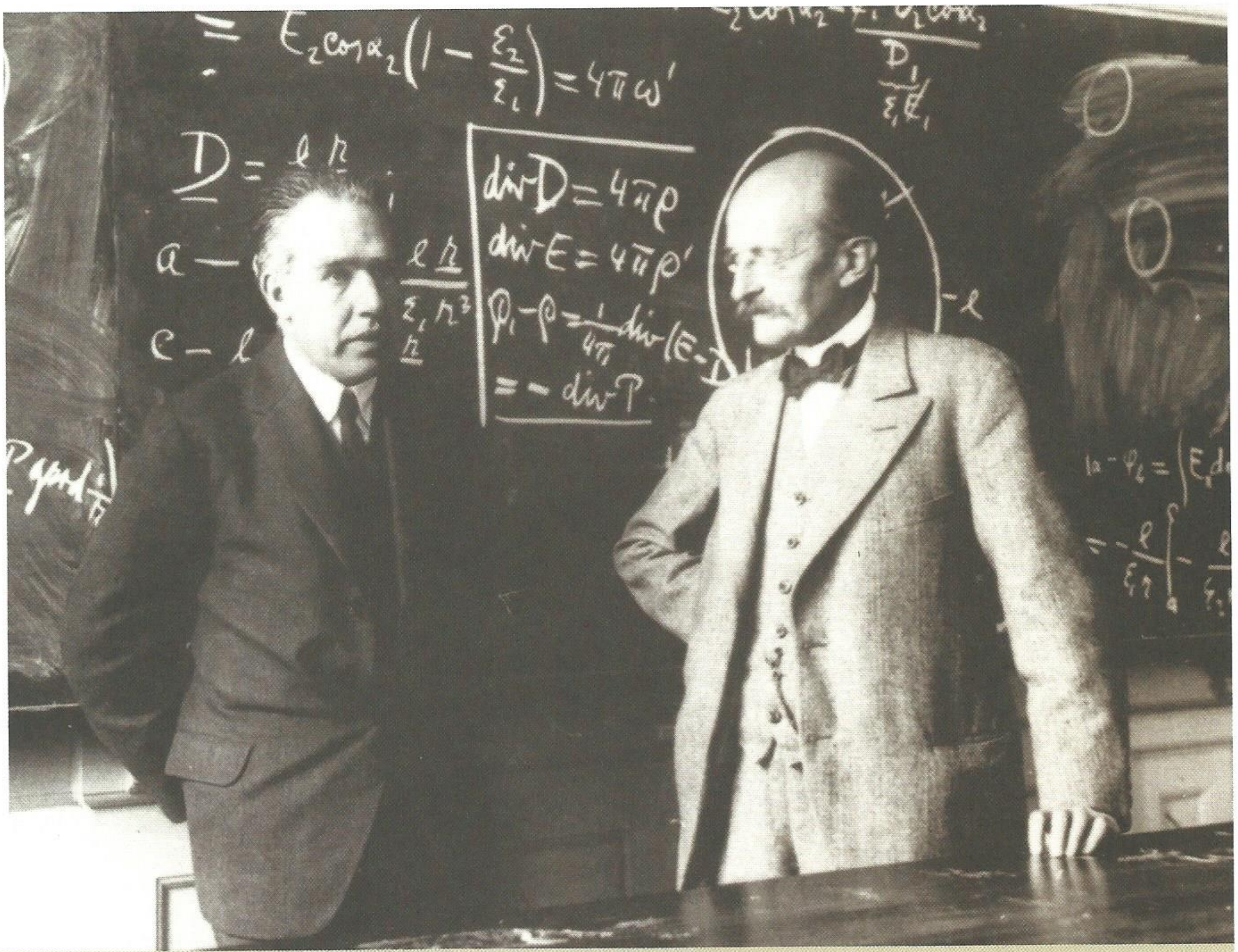
Rutherford's laboratory in Manchester just after Rutherford proposed the nuclear model of the atom, Bohr seized upon it because its radical mechanical instability made it a promising candidate for repair by a quantum hypothesis. Bohr stabilized the Rutherford atom by supposing that it could exist in various "stationary states" constrained by certain quantum rules but otherwise governed by the laws of classical mechanics. However, the laws of mechanics do not hold for the transition of the system between two stationary states during which the atom radiates a quantum of energy $h\nu$ equal to the difference in energy between the two states. On Bohr's theory, radiation is not emitted (or absorbed) in the continuous way assumed by Maxwell-Lorentz electrodynamics.

Bohr's first postulate, which limited the validity of classical mechanics in the atomic domain, restricted the angular momentum of each atomic electron to an integral multiple of $h/2\pi$. The second postulate, which denied the validity of classical electrodynamics for radiative processes in atoms and made the frequencies of atomic spectral lines different from the orbital frequencies of the electronic motions, required surrendering the classical connection between the frequency ν of the emitted radiation and the mechanical frequency of the electron in its orbit.

With the help of these quantum rules, Bohr accounted for the phenomenological regularities that had been discerned in the hydrogen spectrum, in particular, the Balmer formula for transitions to the $n = 2$ level, and also, and more dramatically, for the spectrum of ionized helium (1913–14). During World War I, Arnold Sommerfeld generalized Bohr's postulates to elliptical electron orbits and then to motions in three dimensions. He recorded his success in calculating regularities in doublet and triplet spectra, in the Zeeman effect, and in x-ray spectra in a long book, *Atombau und Spektrallinien* (first edition 1919), with which all physicists interested in quantum and atomic physics during the early 1920s began their work.

In the early 1920s, Bohr gave a phenomenological explanation of the periodic table based on the occupancy by electrons of Coulomb-like orbits in multi-electron atoms. Thereafter, many theorists tried to justify Bohr's explanation, but, except for Wolfgang Pauli's formulation of the exclusion principle early in 1925, none of their efforts provided a stable foundation for the dynamics of atoms. They were seminal, however, in that they made manifest the problems a more complete quantum mechanics would have to solve.

In 1917, Einstein took what in retrospect was an important step toward this mechanics. Still flirting with the corpuscular nature of radiation, Einstein introduced the concept of the probability for the spontaneous emission of a light quantum by a "molecule" in a transition from one state to another. The concept allowed an easy derivation of Planck's blackbody formula. In 1923, Arthur Holly Compton's experiment on the scattering of X rays by electrons indicated that the shift in the wave length of the scattered



Two pioneers of quantum physics, Niels Bohr (1885–1962) and (on the right) Max Planck (1858–1947), in 1930, not lecturing on quantum physics

X ray and the recoil energy of the electron could be derived on the assumption that the X rays acted as particles with energy $h\nu$ and momentum $h\nu/c$ (c the velocity of light). The positive result of the Compton experiment led Einstein to declare that there are "two theories of light, both indispensable, and without any logical connection." The corpuscular viewpoint accounted for the optical properties of atoms, whereas macroscopic phenomena like diffraction and interference required the wave theory of light. The two theories coexisted without any resolution during the early 1920s.

Another important guide to a more powerful quantum physics was the correspondence principle Bohr refined between 1913 and 1918. It stated that the frequencies calculated by Bohr's second postulate (during "quantum jumps") in the limit where the stationary states have large quantum numbers that differ very little from one another will coincide with the frequencies calculated with the classical theory of radiation from the motion of the system in the stationary states. Bohr's assistant Hendrik Kramers cleverly applied the correspondence idea to compute the intensity and polarization of the light emitted from simple atoms. Kramers and Werner Heisenberg extended the same idea to the dispersion of light and worked out ways to translate classical quantities involving a single stationary state into quantum mechanical quantities involving two or more states. Max Born, Heisenberg's teacher at the University of Göttingen, called for a "quantum mechanics" for calculating with the quantum mechanical quantities directly. That was in 1924. In less than a year, Heisenberg provided him with one. Its guiding principles were satisfaction of Bohr's correspondence principle (in the appropriate limit the theory should yield the classical results); recognition that the troubles of the "old quantum theory" arose primarily from breakdown of the kinematics underlying classical dynamics; and restriction of the theory to relations between observable quantities.

Born, Heisenberg, and a fellow student of Heisenberg's, Pascual Jordan, soon developed the new mechanics into an elaborate mathematical formalism. They built a closed theory that displayed strikingly close analogies with classical mechanics but at the same time preserved the characteristic features of quantum phenomena. Their work laid the foundations of a consistent quantum theory but at the price of relinquishing the possibility of giving a physical, visualizable picture of the processes it could calculate. Hence the relief felt by Planck, Einstein, and Lorentz when Erwin Schrödinger, who followed a route entirely different from Heisenberg's, began to publish his wave mechanics in 1926. It seemed to avoid the unconventional features of Heisenberg's formulation and rested on more traditional foundations and easier calculations: variational principles, differential equations, and the properties of waves.

Schrödinger had followed up insights and suggestions by Louis de Broglie and Einstein. In 1923, de Broglie published an idea that was the obverse of Einstein's attribution of particle properties to wave radiation—to endow discrete matter with wave properties.

By following sometimes fanciful analogies and the principle of relativity, de Broglie associated a wave of frequency ν and wavelength λ with a particle of momentum p and energy E according to $\nu = E/h$, $1/\lambda = p/h$. He thus extended the particle-wave duality of radiation to matter. Knowing the wavelength, Schrödinger soon found an appropriate differential equation for a wave of amplitude Ψ. He interpreted the Ψ function as describing a real material wave and considered the electron not a particle but a charge distribution whose density is given by the square of the wave function. In a short paper dated June 1926, Born rejected Schrödinger's viewpoint and proposed a probabilistic interpretation for the Ψ function. He stipulated that the wave function $\Psi(x, f)$ determines the probability of finding the electron at the position x at time t. In 1927, two different sets of experimentalists—George P. Thomson (the son of Joseph John Thomson) in Britain and Clinton Davisson and Lester Germer in the United States—detected diffraction patterns from an electron beam.

Several physicists proved in 1926 that wave mechanics gave the same numerical answers as the "matrix mechanics" of Born, Heisenberg, and Jordan. Together they are known as quantum mechanics. In contrast to classical physics, which contained no scale and was assumed to apply both in the micro and macro domain, quantum mechanics asserted that the physical world presented itself hierarchically. Certain constants of nature layered the world. As P. A. M. Dirac emphasized in the first edition of his *Principles of Quantum Mechanics,* Planck's constant allows the parsing of the world into microscopic and macroscopic realms.

The conquest of the microrealm during the first years after the invention of quantum mechanics stemmed from the confluence of two factors: the apperception of an approximately stable ontology of electrons and nuclei, and the formulation of the dynamical laws governing the motion of electrons and other microscopic particles moving with velocities small compared to the velocity of light. "Approximately stable" meant that electrons and (non-radioactive) nuclei, the building blocks of atoms, molecules, simple solids, could be treated as ahistoric objects, with physical characteristics seemingly independent of their mode of production and lifetimes effectively infinite. These electrons and nuclei behaved as if they were "elementary," almost point-like objects specified only by their mass, their intrinsic spin, electric charge, and magnetic moment. In addition, the members of each species were indistinguishable: all electrons are identical, as are all protons, and all (stable) nuclei of a given charge and mass when in their ground state. Their indistinguishability implied that an assembly of them obeyed characteristic statistics depending on whether they had integral or half odd integral spin (measured in multiples of $h/2\pi$). Bosons (particles with zero or integral spins) can assemble in any number in a given quantum state. Fermions (particles with half odd integral spins) do not share a quantum state. A one-particle quantum state can be characterized either by the position and the spin state of the particle or by its momentum and its spin state. Thus no two identical Fermions can be at the same position if they have the same spin. More generally, the wave function describing a system of identical bosons remains unchanged under the interchange of any two particles, whereas that describing fermions changes sign under such a transposition.

The quantum mechanical explanation of chemical bonding resulted in a unification of physics and chemistry. In 1929, following the enormous success of nonrelativistic quantum mechanics in explaining atomic and molecular structure and interactions, Dirac, a main contributor to these developments, declared that "the general theory of quantum mechanics is now almost complete." Whatever imperfections still remained were connected with the synthesis of the theory with the special theory of relativ-

Physicists at the Solvay Conference of 1927, the fifth in the series of high-level meetings begun in 1911 and sponsored by the Belgian industrialist Ernest Solvay (1838–1922). The conferences considered pressing problems in physics; that of 1927, attended by Einstein, Bohr, Pauli, Dirac, Marie Curie, and Louis de Broglie, discussed the then-new quantum mechanics.

ity. But these were of no importance in the consideration of atomic and molecular structure and ordinary chemical reactions. "The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble." Dirac's assertion may still have the validity it had, but, as emphasized by Phillip Anderson, "the reductionist hypothesis does not by any means imply a 'constructionist' one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society. The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity." Still, physics can be regarded as more foundational (not fundamental) than chemistry because the laws of physics encompass in principle the phenomena and the laws of chemistry.

J. L. HEILBRON

QUARK. During the 1950s and 1960s, progress in classifying and understanding the phenomenology of the ever increasing number of hadrons (strongly interacting microscopic particles) came not from fundamental theory but by shunning dynamical assumptions in favor of symmetry and kinematical principles that embodied the essential features of a relativistic quantum mechanics.

In 1961, Murray Gell-Mann and Yuval Ne'eman independently proposed classifying the hadrons into families based on a symmetry later known as the "eightfold way." They realized that the mesons (hadrons with integral spins) grouped naturally into octets; the baryons (heavy hadrons with half integral spins) into octets and decuplets. The "eightfold way" can be represented mathematically in three dimensions, a property that led Gell-Mann, and independently George Zweig, to build hadrons out of three elementary constituents. Gell-Mann called these constituents "quarks" (from a line in James Joyce's *Finnegans Wake,* "Three quarks for Muster Mark!"); Zweig called them aces. The elaboration of the quark scheme is briefly indicated here as an indication of the methods and madness of elementary particle physics.

To account for the observed spectrum of hadrons Gell-Mann and Zweig defined three "flavors" of quarks (generically indicated by q), called up (u), down (d), and strange (s), each with spin $\frac{1}{2}$ but differing in two other quantum numbers (isotopic spin and strangeness) that defined them. Ordinary matter contains only u and/or d quarks. ("Strange" hadrons would contain strange quarks.) The three quarks had two other features: a baryonic mass of $\frac{1}{3}$, and an electrical charge of $\frac{2}{3}$ (for the u) and of $-\frac{1}{3}$ (for the d and s) those of the proton. This last feature startled physicists who had no experimental evidence for any macroscopic object carrying a positive charge smaller than a proton's or a negative charge smaller than the electron's.

Since a relativistic quantum mechanical description implies that for every charged particle there exists an "antiparticle" with the opposite charge, Gell-Mann and Zweig provided for antiquarks (generically denoted by $\bar{q}$) having an electric charge and strangeness opposite to those of the corresponding quarks.

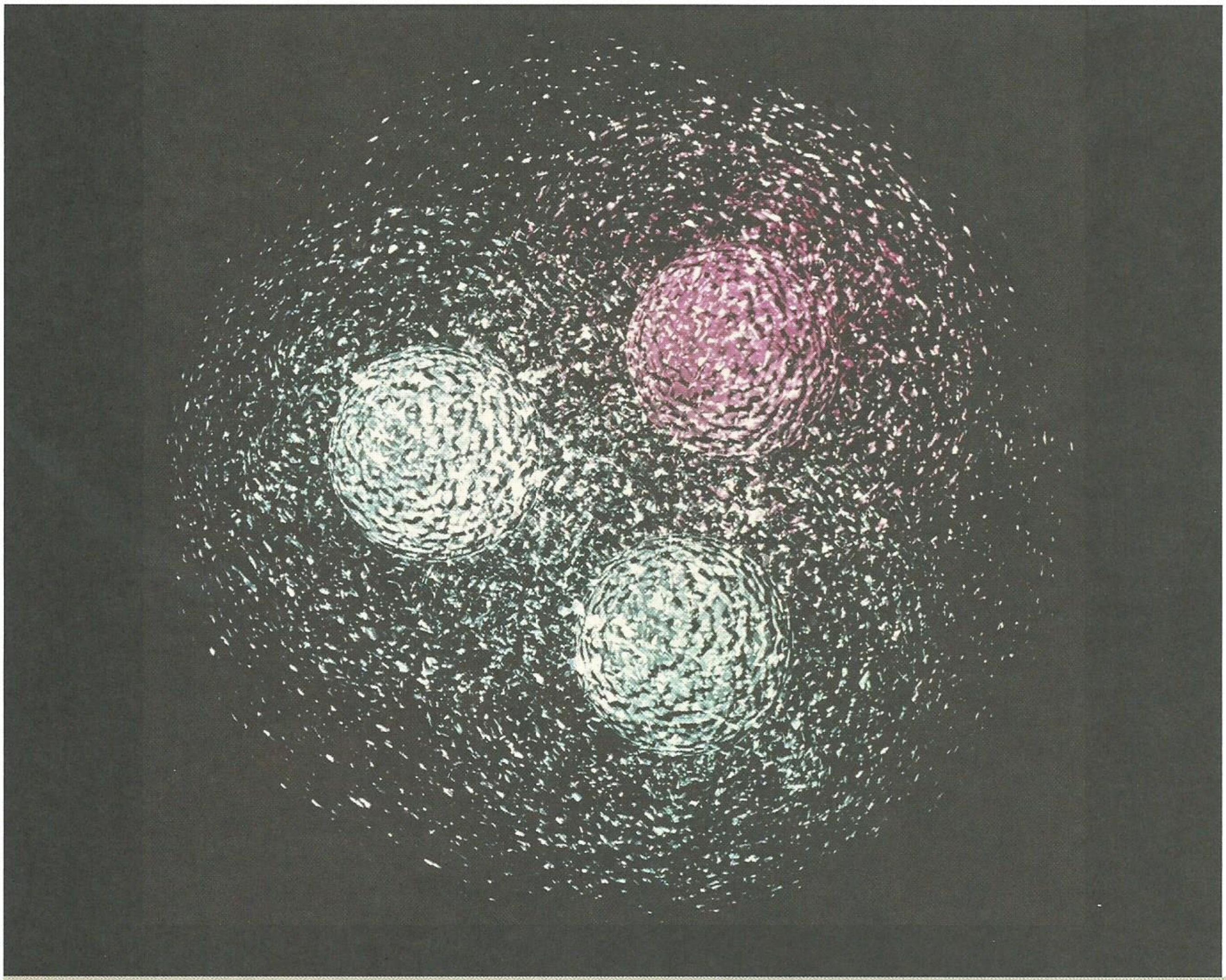
Quarks bind together into hadrons as follows. An up and an antidown quark make a positive meson; two ups (with electrical charge $\frac{4}{3}$) and a down (with electrical charge $-\frac{1}{3}$), a proton. All baryons can be made up of three quarks, all mesons of one quark and one antiquark. That, however, did not provide quite enough possibilities so quarks had to have another attribute, which, in the playful quark nomenclature, was called "color." Quark color comes in three varieties (sometimes taken to be red, yellow, and blue), each of which can be "positive" or "negative." Quarks carry positive color charges and antiquarks carry negative ones. The observed hadrons have no net color charge.

In the late 1960s, the Stanford Linear Accelerator (SLAC) could produce electrons of sufficiently high energy to probe the internal structure of protons. If the proton's charge were uniformly distributed, penetrating electrons would tend to go through it without being appreciably deflected. If, on the other hand, the charge was localized on internal constituents, then—in analogy to Ernest Rutherford's demonstration of the atomic nucleus—an electron that passed close to one of them would be strongly deflected. The SLAC experiments showed this effect, which prompted Richard Feynman to suggest that the proton contained pointlike particles with spin $\frac{1}{2}$, which he called "partons." The partons soon were assimilated to the quarks, although they (the partons/quarks) appeared to be too light and too mobile to make up protons. These difficulties were eventually resolved.

The discovery in November 1974 of the J/Ψ meson gave further support for the quark picture and reason to accept a fourth quark with a new flavor, "charm" (denoted by *c)*, whose existence had been proposed by Sheldon Glashow and others in 1964 and, with greater insistence, in 1970. The J/Ψ (its two names resulted from its simultaneous discovery by two different groups) appeared to be a bound state of c and $\bar{c}$. The discovery of November 1974 revolutionized high-energy physics by establishing the representation of hadrons as quark composites. As the number of hadrons grew, however, the scheme had to be extended by the addition of the "bottom" (or "beauty," *b)* quark in 1977 and the "top" (*t*) quark in 1994. Each successively discovered quark has a larger mass than its predecessors on a scale in which the *u* weighs 1, the *d* weighs 2, the *s* 36, the *c* 320, the *b* 960, and the *t* 34,800. They all have spin $\frac{1}{2}$; partake in the strong, electromagnetic, and weak interactions; and come in pairs: up and down (*u, d),* charm and strange *(c, s),* and top and bottom *(t, b)*. The first member of each pair has electric charge $\frac{2}{3}$ and the second $-\frac{1}{3}$. Each flavor comes in three colors.

If hadrons are made up of fractionally charged quarks, why have fractionally charged particles not been observed? Even if a plausible mechanism could be devised for confining quarks, what reality can be attached to them as constituents of hadrons if they can never be observed empirically? Quantum chromodynamics (QCD), which emerged a decade after the introduction of quarks, explained how quarks could be so strongly bound that they could never escape, while nevertheless behaving as quasifree particles in deep inelastic scattering.

Silvan S. Schweber



Quark structure of the proton. The quarks are the globules, green for the up quark (charge 12/3), pink for the down quark (charge -1/3), They are held together by the strong nuclear force conveyed by a cloud of virtual gluons.

R

RADIOACTIVITY. Studies in radioactivity produced the scientific research fields of nuclear physics, cosmic-ray physics, and high-energy physics, and also nuclear chemistry, nuclear medicine, and nuclear engineering. Beginning in 1940 with the isolation of neptunium and plutonium, the creation of short-lived transuranium elements extended the periodic table of the chemical elements into new territory.

That radioactivity has rested in the shared disciplinary terrains of physics and chemistry is indicated by the shared Nobel Prize in physics awarded to its discoverers Henri Becquerel, Marie Sklodowska Curie, and Pierre Curie, and Ernest Rutherford's receipt of the Nobel Prize in chemistry in 1908 for his (and Frederick Soddy's) elucidation of the mechanism of the radioactive disintegration of atoms.

Polish-French physicist-chemist Marie Sklodowska Curie (1867–1934) and her husband, physicist Pierre Curie (1859–1906), in their laboratory in Paris

Becquerel discovered that uranium salts emit radiation by accident while investigating whether naturally phosphorescent minerals produce the X rays discovered by Wilhelm Conrad Röntgen in late 1895. By 1897, Becquerel and others had demonstrated that uranium radiations carry electrical charge, a physical property that led Marie Curie to apply the quartz electrometer (then recently invented by her husband and his brother Jacques-Paul Curie) to a variety of minerals in search of the property that she termed "radioactivity." She identified polonium and radium as radioactive elements in 1898, and André-Louis Debierne discovered actinium in 1899. They and others found that thorium, like uranium, is radioactive.

Rutherford distinguished two kinds of radiation, which he called "alpha" (distinguished by its ready absorption) and "beta" (about one hundred times more penetrating). At the Curies' laboratory in 1900, Paul Villard discerned a gamma radiation from radioactive substances that appeared to behave exactly like X rays. By 1900, Becquerel, Rutherford, and others had established that the beta rays consist of negatively charged particles similar if not identical to electrons. In 1903, Rutherford showed that the alpha rays also carried a charge and so had to be understood as a stream of particles. By 1908, Rutherford and his colleagues had decisive evidence that the *"alpha"* radiations are helium ions. Rutherford and Soddy recognized in 1903 that thorium continuously produces a new radioactive gas (radon), and a second radioactive substance (chemically identical to radium) from which a longer line of radioactive substances descends. They settled on the hypothesis that radioactive decay is accompanied by the expulsion of an alpha or beta particle from the decaying atom and that the decay can be expressed in terms of a half life, defined as the time during which half of the mass of a radioactive element is transformed into a new substance. Rutherford's continuing study of alpha particles and their interactions with matter prompted the experiments that led to his invention in 1910–1911 of the nuclear atom.

By 1912, some thirty radioactive elements had been identified. This achievement derived from the work of Rutherford's groups in Montreal and Manchester; Marie Curie's laboratory in Paris; Otto Hahn and Lise Meitner's work in Berlin; and other investigators, including Bertram Borden Boltwood at Yale University in New Haven. They differentiated natural decay series beginning with uranium (238), actinium (227) or uranium (235), and thorium (232). In 1913 Soddy, Alexander Russell, and Kasimir Fajans independently developed a generalized radioactive displacement law. In 1911, Soddy had noted that loss of an alpha particle produced a chemical element two places to the left of the original in the periodic table. Similarly, Russell remarked that beta decays lead to the next element in the periodic table. Soddy coined the word "isotope" for radioactive elements chemically identical to another element while differing in atomic weight. Several studies confirmed in 1914 that atomic weights of lead derived from radioactive ores varied from each other and from the established value of 207.2.

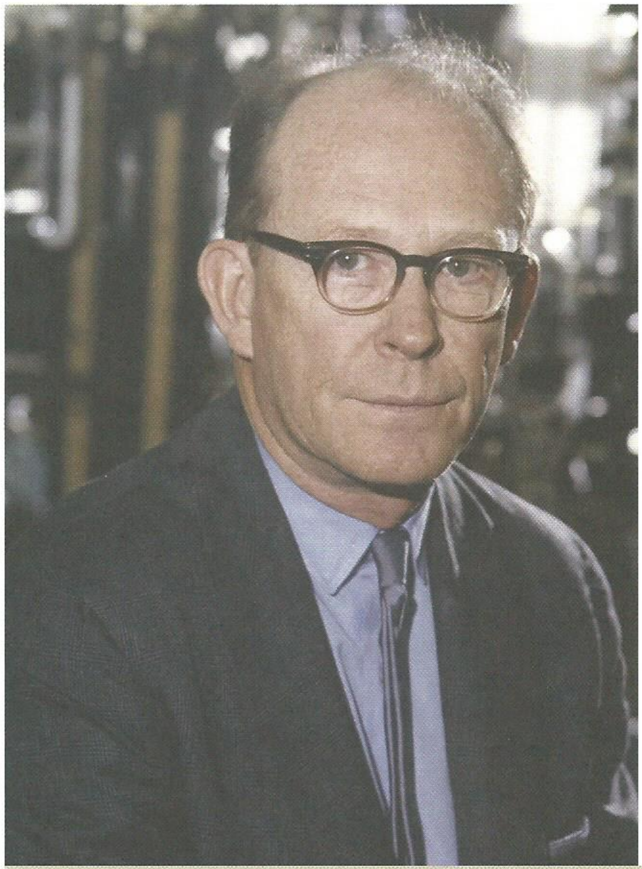
Early methods for detecting radioactivity were both electrical and visual, relying initially on the electrometer and on microscopically observed scintillations of light caused as alpha particles strike zinc sulfide. Electrical methods of detection improved in 1928 when Hans Geiger and Walther Müller succeeded in making a reliable counter using the technique with which Geiger and Rutherford had counted alpha particles before the war. C. T. R. Wilson's cloud chamber, invented in principle in 1899 but not perfected until after World War I, also provided a means of "seeing" nuclear events. Using the older scintillation technique, Rutherford proposed in 1919 that collision of an alpha particle with nitrogen gas resulted in disintegration of the nitrogen atom and expulsion of a long-range hydrogen atom (proton). After automating a cloud chamber, P. M. S. Blackett in 1924 fired alpha particles into nitrogen atoms and obtained dramatic photographs, showing the path of a proton ejected from a recoiling nitrogen nucleus and the capture of the alpha particle by the nitrogen nucleus, creating an isotope of oxygen.

Francis Aston, who began his career as an assistant to Joseph John Thomson, developed a mass spectrograph that provided a photographic record of particles separated by their masses. Aston and others found evidence for isotopes not only among the radioactive and heavy elements, but also among the light elements. The concept of the isotope thus became generalized for all chemical elements.

In 1932, the same year that James Chadwick identified the neutron at the Cavendish Laboratory, John Douglas Cockroft and Ernest T. S. Walton, working with lithium, became the first scientists to split the atom by accelerating protons in a high-voltage, high-tension machine. Ernest O. Lawrence and Milton Stanley Livingston built a circular particle accelerator that provided a rival model for achieving high energies. However, alpha particles from radium provoked the first radioactivity artificially induced by humans. That was in 1934, when Frédéric Joliot and Irène Joliot-Curie produced a radioactive isotope of phosphorus from aluminum.

During the late 1920s and early 1930s, Meitner, Charles D. Ellis, and Enrico Fermi argued over the existence and interpretation of apparent anomalies in the energy in beta decay. Wolfgang Pauli proposed in 1930 that a nuclear particle with a mass similar to an electron but with no charge might be expelled with an electron in beta decay in order to conserve energy in the reaction. Fermi suggested in 1933 that Pauli's little "neutron" be renamed the "neutrino" following James Chadwick's identification of the proton-sized neutral neutron in 1932. Fermi's theory was adopted, although the neutrino eluded detection until 1956.

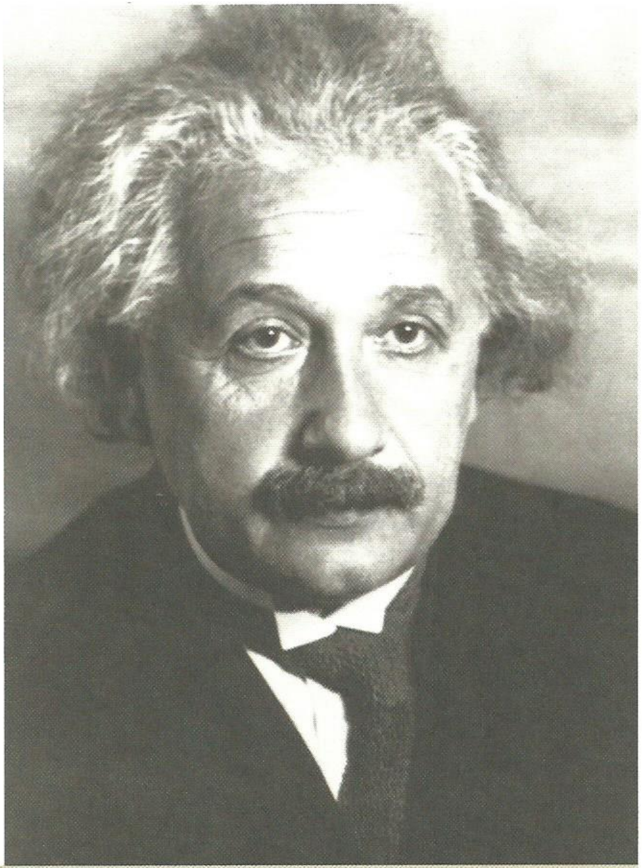
Rays from naturally occurring sources continued to serve nuclear physicists and chemists even in the era of the cyclotron. Fermi and his collaborators irradiated every element they could find with neutrons derived from a radon-beryllium source, discovered the efficacy of slow neutrons in inducing nuclear reactions, and, mistakenly, believed that they had made transuranic elements by shining neutrons on uranium. Meitner, Hahn, and Fritz Strassmann also used neutrons from natural sources in the experiments from which, by the end of 1938, Hahn and Strassmann obtained the results whereby Meitner (by then a refugee in Sweden) and her nephew Otto Robert Frisch deduced the existence of nuclear fission.



Willard Libby (1908–1980), known for his development of radiocarbon dating, for which he received the Nobel Prize in Chemistry in 1960

During the course of the Manhattan Project for the development of uranium and plutonium bombs, the health hazards of radioactivity increasingly came to the fore. Radiations that had been touted since the early 1900s as a general curative and a specific agent against cancer were demonstrated to cause leukemia and other cancer-related diseases. Facial creams and mineral waters, as well as watch dials and curios containing uranium salts, disappeared from store shelves and health resorts in the 1950s as international movements against the atmospheric testing of nuclear weapons gained force from evidence of the hazards of nuclear debris or "fallout." After enthusiasm in the early 1950s for the use of nuclear energy not only as a commercial power source but also for explosives in dam-building and road-building, public suspicion of radioactivity curtailed nuclear energy projects in countries like the United States and Great Britain, although not in France or the Soviet Union.

In chemotherapy and in medical tests, radioactive isotopes continue to serve as tagging or tracer devices for studying the metabolism or pathways of iodine, barium, and other elements in the body. In his first efforts in the 1930s to get large-scale funding for his accelerator program at the University of California at Berkeley, Lawrence emphasized medical applications. Large philanthropies such as the Rockefeller Foundation increasingly turned their funding priorities to medical research in the 1930s. Lawrence and his brother John Lawrence, who served as director of the university's medical physics laboratory, argued for the medical benefits of the production of radioactive isotopes in the



Albert Einstein (1879–1955), invented the theory of relativity at the age of 26

accelerator. One result, phosphorus-32, was used in early attempts to treat leukemia.

Radioactive isotopes had uses beyond medicine. Samuel Ruben, W. Z. Hassid, and Martin Kamen at Lawrence's radiation laboratory used carbon-11 to study the chemistry of carbon dioxide in the photosynthesis of barley and the green algae chlorella. In 1941, Ruben and Kamen identified the radioactive isotope carbon-14 produced from nitrogen in the Berkeley accelerator. Melvin Calvin followed up at Berkeley by using a combination of paper chromatography and radiochemical techniques to unravel in detail the mechanism of photosynthesis.

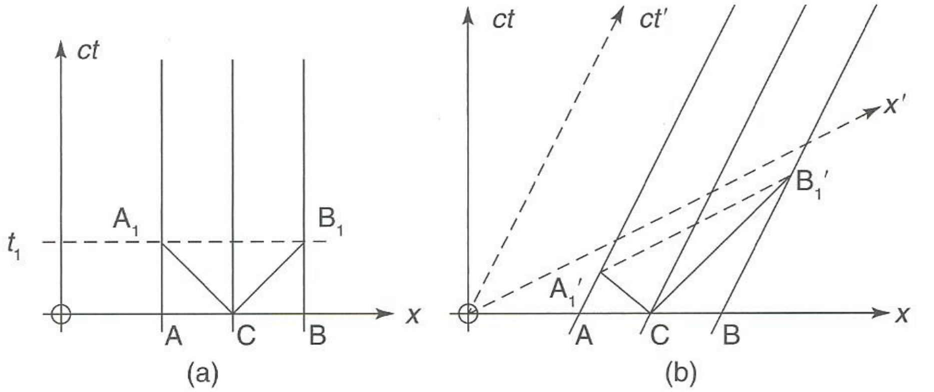
Willard F. Libby attracted more public attention when he showed in 1946 that living matter contains carbon-14, produced by the collision of cosmic ray neutrons with atmospheric nitrogen, which enters the carbon dioxide and carbon monoxide metabolism. Since the quantity of carbon-14 decays after death, Libby's discovery made a brilliant new means of dating very old organic remains.

Since World War II, particle accelerators and nuclear reactors have entirely superseded natural elements as the sources of radioactive materials for laboratory experiments and medical procedures.

MARY JO NYE

RELATIVITY is a theory and program that set the frame of the physical world picture of the twentieth century. Four stages may be distinguished: the invention of the misnamed "special theory of relativity" (SRT), which covered only phenomena observed in bodies moving among themselves with constant relative velocities, in 1905; the recognition of the equivalence of a body's inertial mass (the measure of its resistance to change of velocity) and gravitational mass (the measure of the pull of gravity on it) in 1907; the removal of the restriction to constant velocities in the general theory of relativity (GRT) in 1915; and the application of GRT to cosmology especially in recent decades.

The infelicity of the term SRT involves both the "S" and the "R." It is not "special" but limited, whence the French term "restricted relativity." Again, what distinguishes SRT from classical mechanics is not "relativity"—the idea that the laws of motion look the same in all inertial frames (reference frames moving with respect to one another with constant velocity)—but rather the startling concept that all observers measure the same velocity for light in free space. This distinguishing principle is absolute, not relative. It disagrees with the principle of relativity if, as many physicists believed around 1900, radiation is reducible to mechanics. Einstein insisted on both the absolute and the relative—the constancy of the light velocity and the equivalence of inertial frames—and, in consequence, had to surrender com-



(a)

(b)

The points A and B, at rest in the system *x*, *t*, describe "world lines" parallel to the *ct*-(time) axis: their world position changes in time but not in space. A light signal sent from C reaches them simultaneously (at time t_1) along the "light lines" CA$_1$, CB$_1$, drawn arbitrarily at an angle of 45 degrees to the *x* axis. If A and B move along $_x$ at the speed *v*, they describe world lines inclined to *x* since their world positions change in both space and time. They meet the signals from C at A_1', B_1', that is, at different times measured in the *x*, *t* system. Since relativity requires the signal to be simultaneous in the system *x'*, *t'* in which A and B are at rest, the x' axis must be parallel to A_1B_1; and since, in the *x'*, *t'* system, A and B change their world positions only in time, the *ct'* axis must be parallel to AA*1'* and BB*1'*.

mon intuitions of space and time. One forgone concept was absolute simultaneity.

In the thought experiment Einstein often described, an observer on an embankment sees a light flash from the middle of a passing railroad carriage equipped with a mirror at either end. According to relativity, an observer seated at the center of the car would see the light returned from the mirrors simultaneously. But the observer on the embankment would see the flash from the forward mirror after that from the rear: the light has farther to go to meet and return from the forward than from the rear mirror, and the speed of light by hypothesis is the same in both directions. On a ballistic theory of light, the return flashes occur simultaneously for both parties: to the traveling observer, the light has the same speed in both directions; to the stationary one, the speed in the forward direction exceeds that in the opposite direction by twice the speed of the carriage. Further arithmetic shows that holding to the absolute and the relative simultaneously required that meter sticks and synchronized clocks moving at constant velocity with respect to a stationary observer appear to him to be shorter and tick slower than they do to an observer traveling with them.

Einstein showed that the form and magnitude of these odd effects follow from the stipulation that the coordinates of inertial systems are related by a set of equations that he called the Lorentz transformation. Hendrik Antoon Lorentz had introduced them as a mathematical artifice to make the principle of relativity apply to Maxwell's equations of the electromagnetic field. Einstein now insisted that the Lorentz transformation apply also to mechanics in place of what came to be called the "Galileo transformation" that guaranteed relativity to Newton's laws of motion. The Galilean, which transforms only space, reads, for relative motion at a constant velocity v, $x' = x - vt$, $t' = t$, where the primed letters refer to a coordinate system moving along the x axis of the unprimed system; the Lorentz transformation replaces these relations with $x' = \gamma(x - vt)$, $t' = \gamma(t - vx/c^2)$, $\gamma = (1 - v^2/c^2)^{-1/2}$. When v is negligibly small in comparison with c, the equations have the same form, but not the same meaning, as the Galilean transformation between the same variables. Since the Galilean transformation supports the Newtonian expressions for force, mass, kinetic energy, and so on, replacing it required reworking the formalism of the old mechanics. This labor, in which Max Planck and his student Max von Laue played leading parts, produced expressions differing from the Newtonian ones by factors of γ. A new form of Newton's second law emerged that satisfied the demand of relativity ("remained invariant") under the Lorentz transformation.

As an afterthought, also in 1905, Einstein argued that energy amounts to ponderable mass and vice versa. The relativistic expressions for the momentum and kinetic energy require that, for conservation of momentum to hold, the mass m of an isolated system of bodies must increase when the system's kinetic energy E decreases. The increase occurs at a rate (change of mass) = (change of energy)/c^2, $\Delta m = \Delta E/c^2$. Einstein thus united the previously distinct principles of the conservation of energy and of mass. From a practical point of view, the equivalence of mass and energy as applied to nuclear power is by far the most important consequence of relativistic mechanics.

Relativity had an enormous appeal to people like Planck, who regarded the surrender of common-sense expectations about space, time, and energy as a major step toward the complete "deanthropomorphizing of the world picture" begun by Copernicus. The mathematician Hermann Minkowski declared in a famous speech to the Society of German Scientists and Physicians in 1908 that "space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." He interpreted the Lorentz transformation as a geometrical rotation in his four-dimensional space, whose points represented "world events" and whose lines represented the histories of all the particles in the universe. "The word relativity postulate... seems to me very feeble," he said, "[to express] the postulate of the absolute world," that is, Einstein's theory as geometrized by Minkowski.

Einstein's compulsion to remove the "all too human" from physics and his desire to overcome the limitation of SRT brought him to a more profound generalization than Minkowski's. Taking the equivalence of inertial and gravitational masses as his guide, he worked out by 1911 that gravitational forces should affect electromagnetic fields (for example, by giving radiation potential energy) and deduced that the sun would bend the path of a ray of starlight that passed close to it. But the major conquest wrested from the equivalence of the masses was the elimination of gravity: all freely falling bodies in the same region experience the same acceleration because the presence of large objects distorts the space around them and the bodies have no alternative but to follow the "geodesics"—straight lines in the curved space in which they find themselves. In "flat space-time," without distorting masses, bodies move in inertial straight Euclidean lines. Falling bodies apparently coerced to rejoin the earth under a gravitational force in Euclidean space in fact move freely along geodesics in the local warp in the absolute four-dimensional space-time occasioned by the earth's presence. By 1915, Einstein had found the mathematical form (tensors) and the field equations describing the local shape of space-time that constituted the backbone of GRT and had added two more tests: an explanation of a peculiarity in the orbit of Mercury and a calculation of the effect of gravity on the color of light.

By 1910 or 1911, German theorists had accepted SRT and a few physicists elsewhere recognized its importance. Arnold Sommerfeld grafted it onto Niels Bohr's quantum theory of the atom in 1915–1916, with spectacular results (the explanation of the fine structure of helium). Physicists demobilizing from World War I interested in atomic structure or quantum physics perforce had to learn relativity and, ultimately, to find ways of employing SRT systematically in quantum mechanics. And then the positive results of the eclipse expedition organized by Arthur Eddington and other English astronomers to test Einstein's prediction of the deflection of starlight engaged the public imagination. It appeared that a lone pacifist had by pure thought bettered Newton while most of the world's scientists had devoted themselves to war. Einstein traveled, quipped, became a favorite of newspaper reporters around the world and the bête-noire of anti-Semites back home. He spent the rest of his life, in Berlin and in Princeton, trying to generalize the general by bringing electromagnetism within GRT. But neither his efforts nor those of the few other theorists who thought the game worth the candle managed to reduce electricity and magnetism to bumps in space.

Application to cosmology at first seemed more promising. A solution to the field equations by Aleksandr Friedmann in 1922 indicated the possibility of a finite expanding universe.

The concept agreed with measurements of red shifts in galaxies. The notion of the origin of the universe in a compact space, or "cosmic egg," was bruited by Georges Lemaître in 1927. The resultant Big-Bang universe, with origin in time (initially set at two billion years ago from the accepted value of the Hubble constant), gained some acceptance but little development until the 1960s. Then discoveries in astronomy (quasars, pulsars, supposititious black holes, the cosmic background radiation), laboratory demonstrations of the gravitational red shift and tests with rockets and atomic clocks, and advances in particle physics and the mathematics of gravity made GRT fashionable. Relativistic astrophysics now has the panoply of journals, textbooks, meetings, and money that mark a flourishing science. Although gravity remains outside the unified forces of the Standard Model, the pursuit of the vanishingly small and the ineffably large depend upon GRT for clues to the origin and evolution of the universe.

J. L. HEILBRON

RELIGION AND SCIENCE. Religion and science are both so important and diverse that any attempt to encapsulate their interrelations is bound to fail. Their interaction is also a topic that attracts not only scientists and theologians but also an interested and concerned public. Yet contemporary discussion of religion and science is dominated by partisan writers who promote grand but simplistic theses—some proclaim science to be in perpetual conflict with religion while others posit complete harmony. Moreover, much current discussion draws heavily on such historical episodes as the Galileo affair. The historical study of religion and science has therefore an important contemporary role since it can illuminate the complexity of religion-science interrelations, place the grand popular theses in context, and inject a dose of critical analysis.

Centrality of Religion to the Scientific Revolution

Most of the major figures associated with the rise of modern science in the sixteenth and seventeenth centuries paid close attention to the religious issues and their bearing on science. Thus Francis Bacon could both advocate the separation of science from religion and stress the religious character of science, since the study of nature displayed "the footprints of the Creator." In many cases, too, religion provided the motivation for pursuing science. Johannes Kepler felt compelled to discover the harmony, order, and (ultimately) mathematical laws governing the motions of the planets by the conviction that God had created the universe on a mathematical model. Isaac Newton, who likewise saw the physical world manifesting divine design, adopted a priestly role in determining the laws that God had imposed on matter at the creation. Of the many points of contact between his science and his religion, Newton's innovative concept of "force" possessed strong theological significance since he considered all force to be derived from God. Newton's religious writings were not confined to physicotheology; he also wrote extensively on biblical chronology and prophesy. Nor were his theological views conventional; he

Artist's depiction of Italian astronomer Galileo Galilei's (1564–1642) trial for heresy by the Roman Catholic Church

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tried to conceal his Socinianism (denying the divinity of Christ) in order to avoid the charge of heresy.

The Galileo affair, culminating in his censure by the Roman Catholic church in 1633, has often been portrayed as a conflict between reactionary clerics and the harbinger of scientific progress. Yet, despite the heavy-handed action of a committee of the Holy Office that prohibited Nicholas Copernicus's book, this is an untenable interpretation since not only did many church members support Galileo, especially in the 1610s and 1620s, but he himself also remained a staunch Catholic. The affair raises many substantive issues including the meaning of certain scriptural passages that might bear on astronomy, the relation of empirical knowledge to theology, and the strength of Galileo's arguments in favor of Copernicus's theory. (He failed to prove the truth of the Copernican system.) Other factors that bear directly on this episode were Galileo's ability to create enemies and his refusal to heed Cardinal Robert Bellarmine's advice to treat the Copernican system as a mathematical hypothesis and not as physical truth. Galileo can also be seen as a pawn in the vicious political struggles between the Pope, the Dominicans, and the Jesuits. More controversially, some scholars have interpreted the 1633 trial as the final act in Galileo's long-running battle over atomism with his Aristotelian opponents, who believed it challenged the doctrine of the eucharist. From this perspective the theological acceptability of Copernican astronomy was not at issue. The jury is still out, but historians continue to discover new interpretations of the Galileo affair.

Since early modern science was a product of Christians, some have argued that Christian theology provided the necessary conditions for the rise of science. In particular, Christianity specifies a rational creator who constructed a lawlike universe; these laws can, in turn, be decoded by scientists. While this argument might bear on the rise of science, it fails to explain why modern science was delayed a millennium and a half after the rise of Christianity. Likewise, in a classic article first published in 1938, the sociologist Robert K. Merton attributed the values required for the rise of science in the seventeenth century to the "Puritan ethic"—the assurance of salvation among English Protestants, which found expression in good works, science included. Science was therefore the offspring of a religious system. While his argument applies reasonably well to Britain, it makes it difficult to understand how Catholics contributed to science. Yet many eminent seventeenth-century natural philosophers were Catholic, including Galileo, René Descartes, and Marin Mersenne. Through their schools and colleges, Jesuits were particularly active in teaching modern science. The structure of the Society of Jesus also aided the acquisition of natural knowledge since Jesuits traveled widely and transmitted astronomical data and botanical specimens through their diplomatic channels.

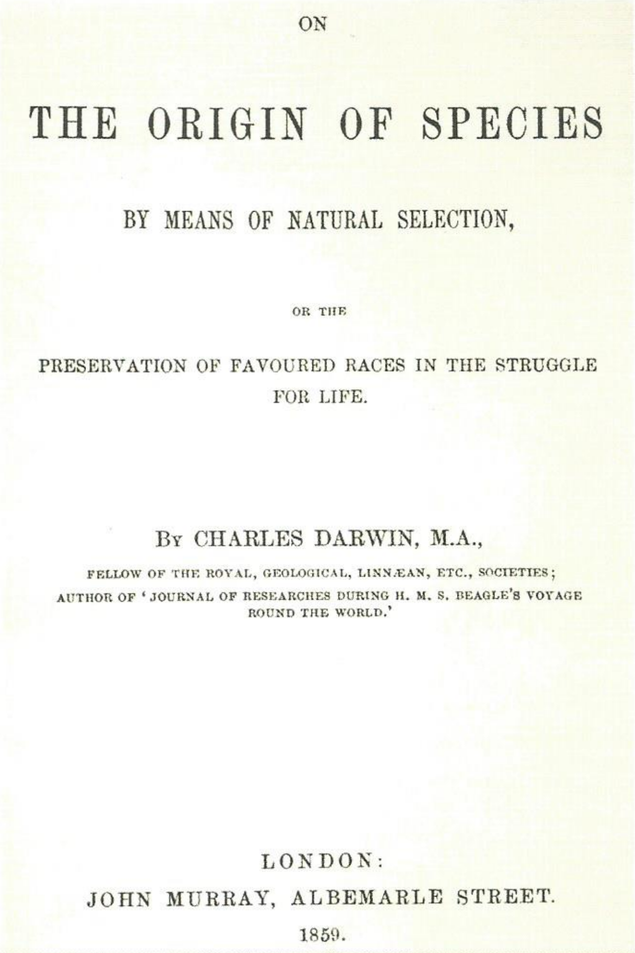
Many of the major intellectual controversies of the seventeenth and eighteenth centuries manifested both religious and scientific dimensions. For example, in the controversy between Gottfried Leibniz and Samuel Clarke (a follower of Newton's), in 1715–1716, Leibniz criticized not only Newton's views about space, time, matter, and force, but also his theology, which emphasized God's will. This is a classic example of a controversy in which scientific and theological issues were thoroughly intermixed. Moreover, "scientists" were not pitted against "theologians"; instead different theologies and different natural philosophies clashed. It is also typical in possessing political and personal connotations, since both Leibniz and Newton were seeking the patronage of the newly enthroned King George I.

Many of those who challenged Newton's science drew attention not only to its scientific difficulties but also to its philosophical and theological defects. For example, Newton considered space to be empty, except for widely dispersed atoms, but his critics seized on emptiness as wasteful and incompatible with a divinely planned universe in which the principle of plenitude applies. Moreover, they objected that Newton's philosophy encouraged pantheism by attributing activity to matter and thereby failing to differentiate the creation from the creator. These critics were not antiscience *per se,* but rather adopted alternative natural philosophies, such as the "scriptural physics" of John Hutchinson, which they considered truly Christian.

Local Contexts

Owing to the diversity of religious traditions, each with its own complex history, it is difficult to draw any global generalizations about science-religion interactions. We should also recognize the existence of local scientific traditions; for example, in France responses to Newton's ideas were affected by both the dominance of Catholicism and by commitments to Cartesian natural philosophy. Much recent research on science and religion has indicated the importance of specific religious and scientific traditions within local contexts. The following examples, which are drawn from English history, illustrate typical loci of science-religion interaction but are not necessarily applicable to other locations. During the eighteenth and nineteenth centuries science proved particularly attractive to religious dissenters, such as Unitarians and Quakers, who emphasized education and promoted science in their schools. For example, the Unitarian Joseph Priestley, best known for his work on gases, was connected with Warrington Academy (county of Cheshire, England) and published a number of educational works, while the Quaker schoolmaster John Dalton began research in meteorology and subsequently developed his theory of the chemical atom. There are many reasons why dissenters were attracted to science: they were not from the land-owning establishment nor did they have access to some traditional routes for social advancement. Instead they were drawn to new and precarious ventures in science and technology—thus many dissenters became prominent in key industries, such as iron smelting and later railway construction. Since dissenters could not graduate from either Oxford or Cambridge Universities until the repeal of the Test Acts in 1871, many studied abroad or in Scotland, where scientific and medical education was of a far higher standard. Thus in many British cities dissenters promoted the provision of hospitals and dispensaries for the poor. Quakers in particular gravitated to pharmacy where their reputation for honesty and their ability at networking worked to their advantage.

The audience for science increased significantly in eighteenth- and nineteenth-century Britain, with a plethora of itinerant lecturers and publications aimed at the upper, middle, and (increasingly) working classes. Often science was presented in a theological frame, a strategy that not only helped legitimate science but also conveyed its intellectually integrity. Thus signs of design, such as the webbed feet of water birds (enabling them to walk on water) or the appropriateness of the distance of the earth from the Sun (preventing the earth from being fried or frozen), were interpreted as evidence of God's wisdom, power, and good-



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE
FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE
ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

Title page of Charles Darwin's *On The Origin Of Species By Means of Natural Selection*, written in 1859

ness. Despite being disparaged by David Hume, design arguments remained very popular, as can be seen from the frequent reprinting of such works as John Ray's *The Wisdom of God Manifested in the Works of Creation* (1691), William Paley's *Natural Theology* (1802), and the Bridgewater Treatises of the 1830s. Design arguments performed many functions and were capable of many different modalities. They could, for example, perform an irenic function by appealing to all denominations. By demonstrating the harmony and integrity of God's creation they also functioned as a creative aesthetic. Many people who would not otherwise have known much science studied it in popular natural theology texts.

Following the French Revolution fear of a popular uprising was fuelled by the materialism and atheism associated with such leading French scientists as Pierre-Simon de Laplace, Jean-Baptiste de Lamarck, and Georges-Louis LeClerc, Comte de Buffon. Over the next few decades the "The March of the Mind," as manifested by Mechanics' Institutes, popular science lectures, and cheap books and periodicals, added to this concern. Attitudes to science became increasingly divergent in Britain. Some saw it as a legitimate hand-maiden of religion, while others conceived it as materialistic and destructive to the old social and religious order. The success of such "alternative sciences" as phrenology (often painted as materialist) and spiritualism (antimaterialist), both of which attracted large followings, further challenged the established church. Secular theories in geology and natural history likewise questioned not only the biblical narrative but also the notion of a divinely crafted universe. By the early nineteenth century, few writers maintained a six thousand year-old Earth, most others being prepared to accept a nonliteral interpretation of Genesis.

The Challenge of Evolution

The publication of Charles Darwin's *On the Origin of Species* in 1859 drew fire from other simmering controversies. As with the Galileo affair, responses to Darwin cannot be reduced to a simple conflict between science and religion—although this interpretation was constructed and widely publicized by some of the protagonists. Historians have uncovered diverse responses from writers holding widely different religious commitments, ranging from those who tried to keep evolution at bay to those who welcomed the new theory as advancing our understanding of how God governs the universe through laws. The short-term impact of evolution on religion is difficult to determine since the "Victorian crisis of faith" had no single cause and the decline in religious observance resulted as much, if not more, from demographic changes and from the impact of such publications as *Essays and Reviews* (1860), which questioned the basis of revealed religion.

In the long term, however, evolution has been central to discussions of science and religion. The *Origin of Species* acted as a rallying point for a number of scientists who not only questioned the truth of Christian belief but also challenged the political power vested in the established church. Thomas Henry Huxley, Joseph Dalton Hooker, John Tyndall, and others—through to Richard Dawkins and Peter Atkins in our own day—have alighted on evolution as the scientific theory with considerable antireligious potential. Following the publication of Darwin's theory it became far more difficult to articulate views of special creation and the argument from design took a severe blow. Nevertheless the polarization that has occurred around evolution is not simply a result of Darwin's theory but also demonstrates the impact of social and political factors. For example, in the southern United States, evolution encountered relatively little opposition until the 1920s when it became the focus for many local grievances and the foe of fundamentalists. The 1925 trial of John Scopes, who defied the law and taught evolution in the public schools of Tennessee, has often been used to symbolize the conflict between science and religion. Opponents of "evilution" have more recently developed "creation science" as an alternative to evolutionary science. Thus they have sought to redefine the conflict between science and religion as a disagreement between two scientific theories.

Darwin's theory also fed into a much more protracted philosophical dispute that challenged Christian ontology. For many Christians, science is suspect if it implies that all phenomena can be reduced to inert matter and a set of laws. Not only does this reductionism portray the universe as inhospitable, but it removes God from nature. Materialists also deny the need for any form of creator, instead attributing natural phenomena to the properties of matter. Huxley, who coined the word "agnostic" to describe those who refused to accept a creator-God owing to lack of evidence, was an ardent materialist. Yet the most conspicuous site of conflict was the meeting of the British Association for the Advancement of Science in 1874 when Huxley's friend John Tyndall devoted his presidential address to the topic. Tyndall traced the history of materialism from the ancients to contemporary ideas about evolution, showing that the advance of science had been achieved through our increasing understanding of matter. Although Tyndall was no naive materialist or reductionist, he was widely attacked as an atheist and for supporting a thoroughly materialistic view of science.

In contrast to Tyndall, religious writers have repeatedly challenged materialism by affirming that the physical world is dependent on God—as creator and/or conserver of the world. Thus Newton asserted that if God were not in continual interaction with the universe it would simply stop, like a clock whose mechanism has run down. More recently, and in very different theological contexts, quantum theory has proved a boon to those who wish to inject mind or spirit into the universe. Scientists of a religious disposition have often been more attracted to such fields as cosmology, astronomy, and physics—as opposed to the biological sciences—where considerable scope exists for natural theological speculation.

In the second half of the nineteenth century, the Roman Catholic church implemented a number of measures that, in the eyes of its detractors and not a few of its members, made it increasingly rigid and inhospitable to new ideas, especially developments in science. Science was made subservient to theology, while scholastic philosophy and the power of the papacy were enhanced. Among the indirect reactions to this increasing conservatism was the publication in 1874 of John William Draper's *History of the Conflict between Science and Religion,* which portrayed Catholicism as the natural enemy of science. In this classic statement of the conflict thesis, science and Catholicism are two opposing forces that have been played out in history. In response to this interpretation, many Catholic scientists, historians, and theologians have tried to rescue the church by offering less antagonistic accounts of the Galileo affair. Particularly since the Second Vatican Council positions have shifted significantly and in 1979 Pope John Paul II conceded that the church had made a mistake. In 1992, following a report by the Pontifical Commission, the church acknowledged that the Galileo affair resulted from "tragic reciprocal incomprehension."

Beyond Christianity

An interesting twist to science-religion interactions has been the development of "scientism," the view that science can be extended beyond its usual disciplinary boundaries to encompass all other areas, religion included. For example, the late nineteenth-century chemist Carl Wilhelm Wolfgang Ostwald advocated a substitute religion based on contemporary scientific ideas, especially thermodynamics. He believed that his new "religion" would fulfill the psychological functions traditionally performed by Christianity, which he utterly rejected. He envisaged a secular festival that would replace Christmas at which candles would be lit and hymns sung in praise of "energy." The example of Ostwald's new religion and the many subsequent versions of scientism raise the question whether it is a religion or an antireligion.

The literature on science and religion has been dominated by writers seeking to defend or attack Christianity. Little attention has been paid to other religious traditions, which have often experienced far less difficulty in relating to mainstream science. In Judaism, for example, there has been relatively little antagonism to science. Jewish participation in science was however often limited by the civil and educational disabilities imposed by the countries in which Jews lived. Paradoxically, in the late nineteenth and early twentieth centuries Jews tended toward science since other professions were closed to them. Thus Jews made up a significant proportion of scientists, especially in German-speaking countries. Many of them were subsequently forced to leave owing first to the economic recession during the inter-war years and later to Hitler's purges. American, British, and Russian science benefited.

China developed independent scientific traditions commensurate with the religious philosophies of Buddhism and Taoism, often emphasizing human harmony with nature rather than nature's exploitation for human ends. Since the seventeenth century, there has been considerable but selective interchange of Western science and technology for alternative medical therapies. Probably the most important contemporary encounter is between Western science and Islam. Drawing on both the Koran and its early encounters with Greek science there is a strong Islamic tradition of analyzing the physical world. Yet the contemporary encounter with Western science is also deeply marked by the various politically charged responses to Western culture and capitalism.

GEOFFREY CANTOR

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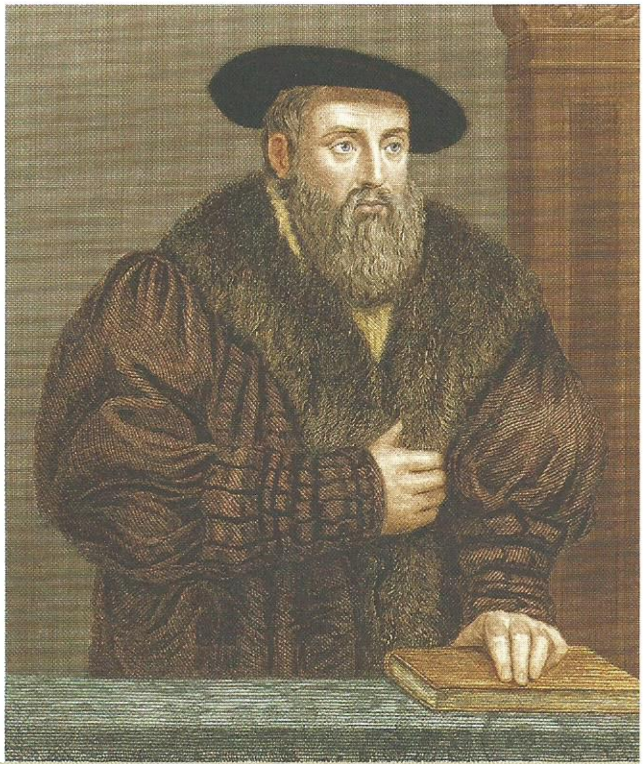
SCIENCE FICTION. Given the human affinity for storytelling, the rise of modern science inevitably prompted narratives involving science. One of the first writers of science fiction was Johannes Kepler, whose posthumously published *Somnium* (1634) explained and defended the heliocentric model of the solar system by describing the astronomical observations of a man transported to the Moon by demons. Unmemorable as literature, *Somnium* indicated that scientific discussions in fictional contexts might have special virtues.

Despite sporadic attention to figures like Kepler and Jonathan Swift for his satirical *Gulliver's Travels* (1726), historians of science fiction emphasize four figures of the nineteenth and early twentieth century as central to its origins and development. They accept Mary Shelley, author of *Frankenstein* (1818), as the first science fiction writer. Jules Verne achieved popular success with adventurous novels featuring new means of transportation and journeys into exotic realms. H. G. Wells effected a brilliant synthesis of earlier writers' generic models—including Shelley's Gothic horror, Verne's travel tales, Swift's satire, and Edward Bellamy's utopia *Looking Backward* (1888)—to produce several famous novels, including *The Time Machine* (1895), *The Island of Dr. Moreau* (1896), *The Invisible Man* (1897), *The War of the Worlds* (1898), and *First Men in the Moon* (1901), which established patterns for all later science fiction writers. Hugo Gernsback named the genre "science fiction" and transformed it into a recognized category of literature by editing the first science fiction magazine, *Amazing Stories,* beginning in 1926.



Johannes Kepler (1571–1630), the German astronomer who devised the three fundamental laws of planetary motion

Despite Gernsback's lasting influence on the American variety of science fiction, not all writers and editors shared his devotion to science, and the genre expanded and diversified in magazines of the 1930s and 1940s. Like Gernsback, editor John W. Campbell, Jr., of *Astounding Science-Fiction* favored scrupulously scientific stories, or "hard science fiction," but other magazines like *Planet Stories* emphasized the subgenre of "space opera," exciting interplanetary adventures that might display little awareness of scientific realities. Such stories were also prominent in the science fiction films and television programs of the 1950s and 1960s. Despite the genre's burgeoning presence in these and other media like comic books and (later) video games, science fiction enjoyed little success in theater and radio, with exceptions like the depictions of humanoid robots in the play *R.U.R.* (1920) by Czech writer Karel Čapek and the 1938 radio adaptation of Wells's *The War of the Worlds* (1898).

After World War II, English-language science fiction dominated the world, led by major writers like Isaac Asimov, Arthur C. Clarke, Robert A. Heinlein, and Frank Herbert, all capable of crafting both realistic accounts of near-future developments and expansive visions of humanity's distant future. Science fiction that stressed literary values more than science was produced by Ray Bradbury, Kurt Vonnegut, Jr., Philip K. Dick, Ursula K. Le Guin, J. G. Ballard, Harlan Ellison, Samuel R. Delany, and other writers who sometimes labeled their work "speculative fiction." Non-English science fiction usually dwelt more on satire than on science, though intriguing speculations about alien life and technological breakthroughs came from Russia's Boris and Arkady Strugatsky, Poland's Stanislaw Lem, and Japan's Kobo Abe.

In the 1970s and afterwards, the *Star Trek* television series and *Star Wars* films brought new popularity to space opera, in print and film. New schools of science fiction emerged, including outspoken feminists led by Joanna Russ and Pamela Sargent, and "cyberpunks" like William Gibson, Bruce Sterling, and Neal Stephenson, who were fascinated by technology and committed to literary sophistication. Other distinctive new voices like Kim Stanley Robinson and Octavia E. Butler resisted easy categorization.

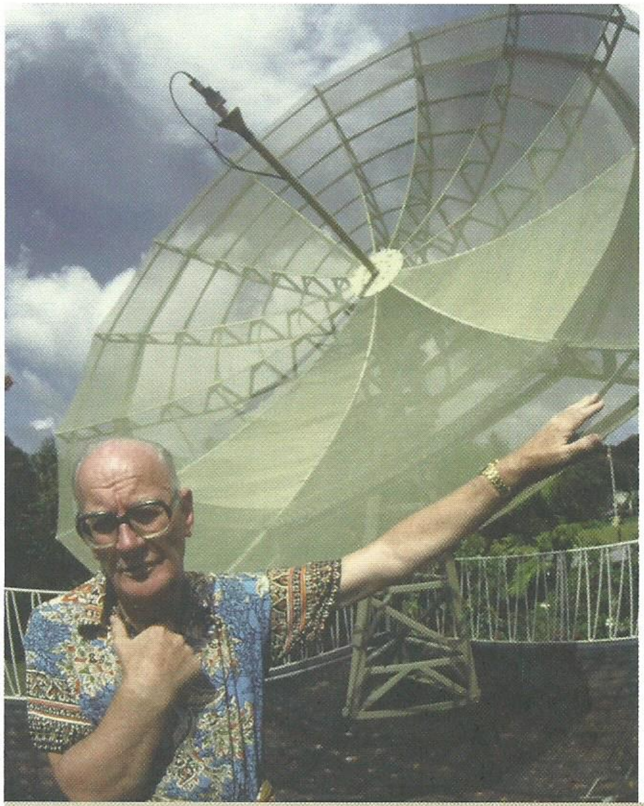
While science fiction has grown more variegated to appeal to wider audiences, many still believe that science fiction should have a strong relationship with the scientific community. In his essay "Old Legends" (1995), physicist and writer Gregory Benford reports that many scientists—himself, Freeman Dyson, Stephen Hawking, Edward Teller, Steven Weinberg, and researchers of the Manhattan Project and at Livermore National Laboratory—often read and discussed science fiction stories. Carl Sagan, who later advocated scientific searches for alien life, stood under the stars as a child and longed to be transported to Mars like John Carter, hero of several novels by Edgar Rice Burroughs. Leo Szilard read Wells's *The World Set Free* (1913), which first predicted atomic bombs, during the 1930s, when he was developing the idea of a chain reaction leading to an explosion. Gerald Feinberg first envisioned faster-than-light tachyons after reading "Beep" (1954) by James Blish. And following Kepler's example, some scientists, including Fred Hoyle, Marvin Minsky, Szilard, and Sagan, have moved from reading to writing science fiction.

Gernsback had expressed hopes of institutionalizing science fiction as a stimulus to scientific advances: Writers would send stories with promising ideas to magazines, experts would review submissions to ensure their scientific plausibility, and scientists reading the stories would be inspired to build new inventions. Although Gernsback's plans (which included allowing science fiction writers to patent their ideas) have been ridiculed, the notion of mining science fiction for potentially useful concepts endured. In 2000, the European Space Agency's Innovative Technologies from Science Fiction project enlisted scholars to compile ideas from futuristic stories that might lead to new scientific initiatives. A possible illustration of the process would be the artificial hands used to manipulate radioactive material, named "waldoes" to acknowledge their first appearance in Heinlein's "Waldo" (1942). The terms "astronaut," "genetic engineering," "robotics," and "terraforming" also originated in science fiction stories.

Campbell extended Gernsback's theories to suggest that development of scientific ideas in narrative form could provide scientists and policymakers with important insights not obtainable from everyday scientific activities. Campbell's suggestion might apply to works like Heinlein's "Solution Unsatisfactory" (1940) and Lester del Rey's "Nerves" (1942), which predicted not only atomic energy but also the technical and political problems it might engender.

Along with its potential power to predict future inventions and their effects (which many would argue is illusory or unimportant), science fiction may also encourage worthwhile exercise in scientific thinking. The spectacular but scientifically plausible new worlds created by masters of science fiction like Hal Clement and Larry Niven enable thoughtful readers to critique or expand upon the scientific logic deployed. When Niven posited a huge artificial ring around a star in *Ringworld* (1970), students analyzing the concept determined that such a structure would not be mechanically stable, which prompted Niven to add "stabilizing rockets" to the construct in *Ringworld Engineers* (1979). Other provocative subjects for informed scrutiny surfaced in Hoyle's *The Black Cloud* (1957), featuring an intelligent cloud traveling through space, and Robert F. Forward's *Dragon's Egg* (1980), describing the evolution of life on the surface of a neutron star. Science fiction might also be lauded for sustaining interest in the possibility of time travel during the decades when working scientists dismissed the idea as fanciful.

In addressing the general public, science fiction has affected attitudes toward science and influenced policy decisions. Gernsback hoped science fiction would educate readers about science and encourage them to support scientific progress. At times it has done so. In the 1950s, novels like Clarke's *Prelude to Space* (1951) and films like *Destination Moon* (1950) portrayed and advocated human flight into space; in the 1970s, the American government exploited the popularity of *Star Trek* to publicize the space shuttle. The National Aeronautics and Space Administration (NASA) named its prototypical shuttle the Enterprise after the ship in *Star Trek* and enlisted cast members for promotional films and appearances. H. Bruce Franklin's *War Stars* (1988) suggests that an American tradition of future-war novels featuring successful superweapons may have inspired Harry S. Truman to use atomic weapons.

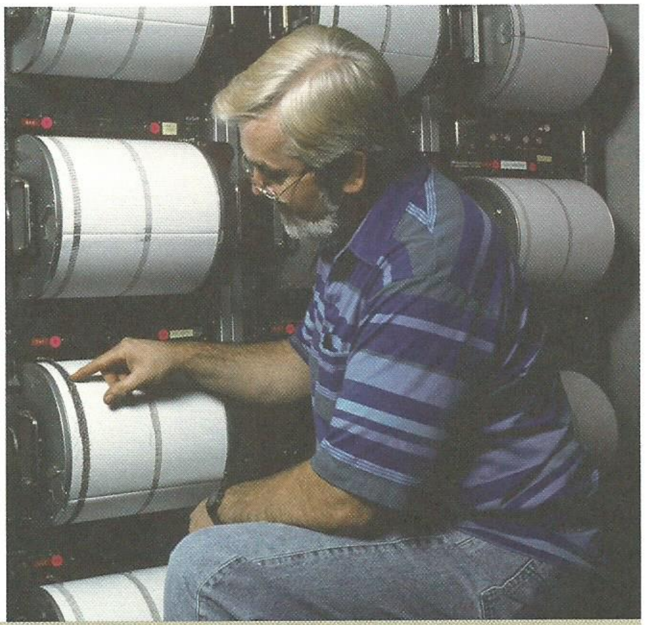

Arthur C. Clark (1917-2008), writer and scientific visionary, pictured at his home in Sri Lanka

Science fiction works have also helped to hinder or prevent scientific developments. The nightmarish scenario of a totalitarian government's employing ubiquitous surveillance technology in George Orwell's *Nineteen Eighty-Four* (1947) sparked determined efforts to prevent that future from occurring. Likening plans for space-based antimissile devices to the death rays in the space battles of *Star Wars*, opponents derided the proposals as "Star Wars" systems. And since science fiction, particularly the celluloid variety, has perpetuated stereotypical images of "mad scientists" who thoughtlessly pursue dangerous projects leading to monsters, mutations, and mayhem, researchers seeking to bioengineer new plants and animals are obliged to proceed carefully, anticipating public fears of new "Frankenstein monsters."

GARY WESTFAHL

SEISMOLOGY, a branch of geophysics, examines the behavior and products of elastic (seismic) waves traveling within the earth. Earthquakes are the most significant generators of these waves. Other sources include volcanic eruptions, explosions (including nuclear explosions), and meteorite impacts. Trucks, trains, and thunder produce seismic "noise." The discipline of seismology covers documentation of events and effects (observations, maps, catalogs), instrumentation and analysis, theory and application. Because large earthquakes can be detected worldwide, the science is international.

Since ancient civilizations arose in earthquake-prone country, a long history of observation and speculation about



A geologist at the US Geological Survey monitors seismograph readings from a recording station in California

earthquakes exists. Aristotle proposed a classification of earthquakes while the Chinese philosopher Chang Heng is credited with designing an inertial seismoscope in A.D. 132 that could determine the source direction of an earthquake. Many early treatises attributed earthquakes to the movement of air or water vapor within the earth. The role of rock fracturing in earthquake generation was not realized until the mid-nineteenth century.

The great Lisbon earthquake and tsunami (tidal wave) of 1755 mark the beginning of the systematic study of earthquakes in western science. For the next century or so, studies of earthquakes consisted primarily of observations of how earthquakes behaved, their geological effects, catalogs of historical events, and continued speculation about their causes. By the early eighteenth century, inertial seismoscopes in Europe included pendulums and bowls of liquid mercury. Earthquake catalogs and other regular observations of earthquakes were widely compiled. By 1840, enough information had accumulated for Karl Ernst Adolf von Hoff to produce the first global historical catalog of earthquakes.

Image made from data collected by satellite radar interferometry of the earthquake at Hector Mine, California, on October 16, 1999. The colored contours indicate displacements in multiples of ten centimeters increasing toward the fault at upper center. The quake registered 7.1 on the Richter scale.

Around 1850, seismology began to take shape as a separate field of inquiry. Robert Mallet studied the great Italian earthquake of 1857 and wrote the landmark *First Principles of Observational Seismology.* Johann J. Noggerath in 1847 first used isoseismals to map earthquake intensity, Luigi Palmieri produced an electromagnetic seismograph first used in 1856, and M. S. de Rossi and François Alphonse Forel cooperated to publish the first widely used, standardized intensity scale in 1883. By the end of the century, scientists were designing the first reliable seismographs (recording instruments). They sought ways to reduce friction between the recording needle and recording paper, to damp triggered motion in the instrument, and to eliminate local disturbance of the mechanism. In 1892, John Milne in Japan produced the first compact, simple (though still not entirely accurate) seismograph. Boris Golitsyn's galvanometric seismograph, perfected in 1911, suspended the pendulum in an electromagnetic field, but largely independently, scientists developed the basic theory of elastic wave behavior. Simeon-Denis Poisson worked out a theory for the primary and secondary (P and S) waves; George Gabriel Stokes and Lord Rayleigh made further contributions; and the effort culminated with the publication of theoretical work on surface and other seismic waves by Horace Lamb in 1906 and A. E. H. Love in 1911.

By the early twentieth century, international cooperation and the standardization of observations worldwide, including accurate timing mechanisms and travel-time tables, allowed the development of new standard scales of magnitude and detailed maps of global seismicity. Using Milne's seismograph scientists in the British empire had set up the first uniform, international network. In the 1930s, Charles Francis Richter and Beno Gutenberg developed a standard scale to measure the relative sizes of earthquake sources, commonly called the Richter scale. It is one of several magnitude scales in use today. Gutenberg and Richter also wrote textbooks that became standards in the field. Seismology figured among the founding six sections at the first meeting of the International Union of Geodesy and Geophysics (IUGG) in 1922. The International Association of Seismology and Physics of the Earth's Interior (the IASPEI), a branch of the IUGG, continues to coordinate international seismological research.

The twentieth century saw major advances in geophysics as a result of the accumulation of seismic data and analysis. In the first half of the century seismologists and geophysicists such as Gutenberg, Richter, Hugo Benioff, Inge Lehmann, Harold Jeffreys, and Francis Birch delineated the interior, layered structure of the earth. By the end of the century investigators were mapping heterogeneity in the earth's mantle and its boundaries using a method called seismic tomography. A second important spin-off followed from the more accurate location (both geographically and within the earth) of earthquake sources and the differentiation of fault motions, known as focal mechanisms. This information played a major role in the development of the theory of plate tectonics. A third area of importance was the investigation of the structure of the crust itself. During World War II, Maurice Ewing and others developed the technology to make seismic investigations offshore. This allowed the mapping of layered strata beneath the sea floor. The investigation of the earth's crustal structure, at ever greater depths and resolution, has continued to the present day, particularly in the field of seismic stratigraphy.

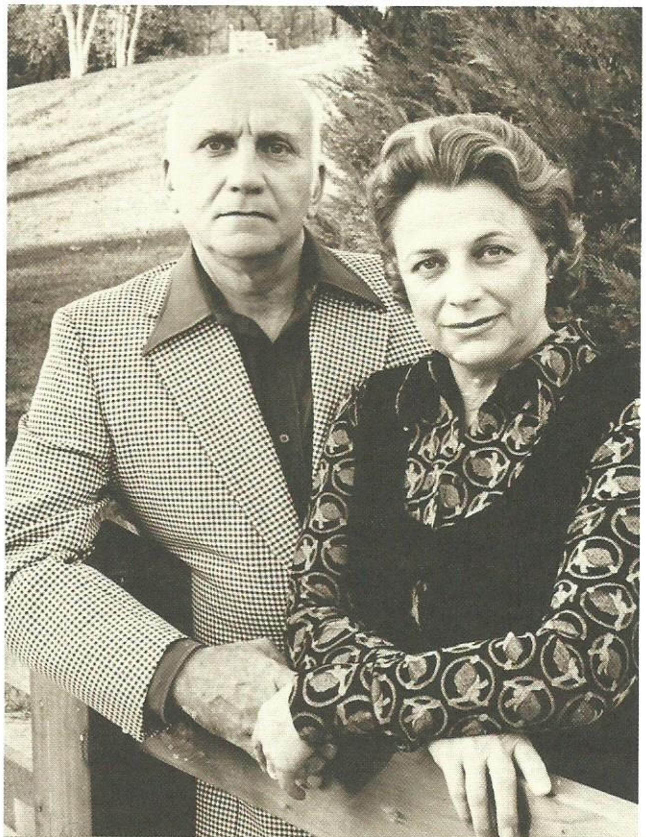
From the 1920s on, seismology has been put to practical uses like the search for oil and gas in the subsurface by using artificial sources of elastic waves, primarily dynamite explosions. Beginning in the 1950s, seismology has been used for monitoring nuclear testing and for understanding other seismic events caused by humans such as those triggered by pumping fluids such as water or oil into or out of the ground. Volcanic seismology has improved to the point that it can help predict volcanic eruptions. While seismologists still cannot predict earthquakes with accuracy, they have done much to explore their preconditions. As human population has increased, more funding has been devoted to earthquake preparedness, including the design of structures, the education of the public, and hazard analysis. In places where the historical record of earthquakes is too short to analyze earthquake probability, workers in the field of paleoseismology use geological evidence to document prehistoric earthquakes.

Satellite and digital technology, notably the Internet, have had major effects on seismology. In 1984, a consortium of American universities founded the Incorporated Research Institutions for Seismology (IRIS) to develop, deploy, and support modern digital seismic instrumentation. By the year 2000, IRIS had more than ninety member institutions and four major programs: the Data Management System (DMS), the Global Seismographic Network (GSN), a program for the study of the continental lithosphere (PASSCAL), and an education and outreach program.

JOANNE BOURGEOIS

SEX. Societal taboos still significantly affect the dispassionate study of sex. Investigations have been discontinuous and scattered, findings contradictory, and samples small and often not directly comparable. There has been little interdisciplinary discussion.

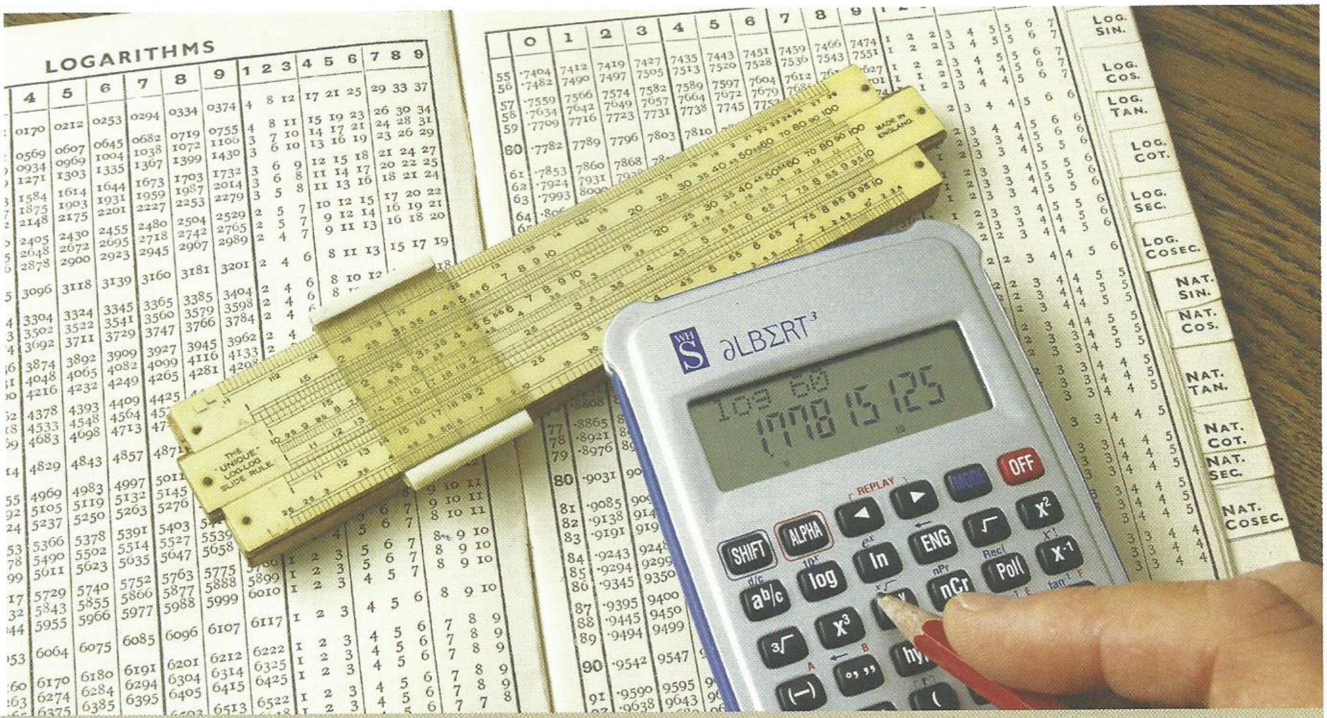
A necessary precondition for a scientific study of sex was the perception that it had medical and social, not just individual moral, repercussions. These became more apparent as urban spaces enabled semivisible homosexual subcultures and other manifestations of "deviancy," providing many opportunities for sexual gratification away from its "legitimate" locus within marriage. By the late nineteenth century, several factors facilitated the emergence of a sexual science. These were a growing awareness of the serious consequences of venereal diseases and the role of accepted sexual mores (the "double standard") in disseminating them; anthropological reports destabilizing assumptions of one "natural" pattern of sexual behavior; increasing refusal among homosexuals to accept stigmatization, with a search for validatory models; and the influence of Darwinism and evolutionary theory in which sexual selection played the central role.



William Howell Masters (1915–2001), American gynecologist, and his wife, psychologist Virginia E. Johnson (b. 1925), who together studied sexual activity under laboratory conditions

In the 1860s, Karl Heinrich Ulrichs, a German lawyer, argued from theories of embryological development that homosexuality was neither a crime nor a disease but an inborn condition whereby one individual might have characteristics of the other gender to the one externally apparent, leading to sexual desire for the same, rather than the other, sex. In the following decades, French psychologist Alfred Binet defined "fetishism," and Italian criminologist Cesare Lombroso's writings on the sexually deviant gained wide currency. The German psychiatrist Richard von Krafft-Ebing's *Psychopathia sexualis* (1886) cataloged a vast variety of deviations; recent scholarship locates him as a champion of the homosexual against the notorious Prussian Code. He listened to and learned from the numerous homosexuals of good social position who consulted him. Magnus Hirschfeld, who argued in early-twentieth-century Berlin for the rights of the "third sex," followed Krafft-Ebing's lead in an even more radical direction.

In Britain, works by self-acknowledged "inverts" such as John Addington Symonds and Edward Carpenter drew on a range of contemporary scientific discourses to reinforce their arguments that homosexuality was not a crime, a disease, a sin, or a vice but "natural" and inborn in certain individuals, even benign in its effects. Havelock Ellis, a friend and colleague of Symonds and Carpenter, gave an exhaustive review of human sexuality in his seven-volume *Studies in the Psychology of Sex* (1897–1928), displaying a grasp of several intellectual disciplines and the international literature. Other significant figures in this endeavor were the Swiss Auguste-Henri Forel and the Russian-German Iwan Bloch. Sigmund Freud took a different approach, penetrating the depths of the human psyche rather than scanning cross-cultural differences. Meanwhile biologists began to investigate the "sexual secretions" significantly later than the products of other endocrine glands. By the early 1930s, they had discovered that no male or female secretion existed; though differing in their proportions, testosterone and estrogen were found in both sexes. In the United States, a few pioneering social



Printed tables, slide rules, and scientific calculators give values for logarithms to ease multiplication and division.

scientists started to survey what people actually did. Alfred Kinsey's huge report of 1948 on the sexual life of the American male revealed the extent of the disjunction between conventional assumptions about sexual life and the doings in the bedrooms of the nation. During the following decade, William Howell Masters and Virginia E. Johnson mapped the orgasm using human subjects in the laboratory.

The advent of the AIDS-HIV epidemic directed attention to the magnitude of ignorance about human sexuality and behavioral motivation. Claims to have discovered the biological basis for sexual orientation or intellectual and behavioral differences between the sexes routinely arrive, receive widespread publicity, and soon fade. In spite of increasingly meticulous attention to the vexed questions of research methodology and problems of population sampling, surveys by social scientists on individual sexual attitudes and behavior continue to be criticized as unrepresentative, methodologically flawed, or based on deceitful responses, and therefore invalid, even though ever since Krafft-Ebing and Ellis, personal testimonies have demonstrated the mismatch between reality and conventional assumptions. As we enter the twenty-first century, sex remains an area of contested knowledge.

LESLEY A. HALL

SLIDE RULE. The slide rule served generations of scientists, engineers, and technical professionals as a quick, convenient, and portable calculating device. First devised in the seventeenth century, it achieved its widest use in the nineteenth and twentieth centuries before being rapidly eclipsed by handheld electronic calculators in the early 1970s.

The most basic of slide rules are particularly suitable for multiplication and division. With additional scales, the instrument can tackle trigonometric problems and higher-order tasks such as the extraction of roots. By modifying standard scales, formulas and constants for a myriad of special-purpose calculations can be incorporated into the design of the slide rule.

Slide rules have been made in a variety of formats, with scales arranged on straight rules, circles, cylinders, and spirals. The key ingredient common to all types is the logarithmic scale. First described by the Scottish mathematician John Napier in 1614, logarithms were quickly adopted and reformulated by his contemporaries in London. Arranged in printed tables, logarithms translated lengthy multiplications and divisions into much simpler additions and subtractions.

Edmund Gunter made the first logarithmic instrument by placing logarithmic scales on a ruler and performing calculations with the help of a pair of dividers. Introduced in 1623, the Gunter rule was soon transformed into a self-contained slide rule by the simple expedient of placing two rules side by side. Although surrounded by considerable controversy, the first to devise this arrangement was probably William Oughtred, who also invented the first slide rule in a circular format.

The slide rule stood briefly at the forefront of innovation in practical mathematics, but soon found its niche as a routine tool for particular trades and professions. Early designs for gauging, excise calculations, and carpenter's work were gradually supplemented by new applications in navigation and surveying. During the nineteenth century, the predominantly British slide rule became a genuinely international instrument. As a general-purpose calculator, its design was standardized, while the number of its specialized uses—from chemistry to monetary calculation—continuously increased.

By the middle years of the twentieth century, slide rules could be found in almost any activity requiring calculation, from engineering construction and electronics to meteorology and black-body radiation. In addition to the professional market, their use in schools created a demand for literally millions of instruments. Traditionally hand-divided on wood, slide rules appeared from the late nineteenth century in celluloid (and other plastics), bamboo, magnesium, and aluminum. New manufacturing methods such as machine dividing and printing increased the accuracy and rate of production.

While efforts were made in the late nineteenth century to produce slide rules operating to four and even five significant figures, precision remained subsidiary to ease of use, low cost, and speed. The introduction of handheld electronic calculators in the 1970s combined these benefits with high precision, and within a very few years the mass market for slide rules collapsed. Some specialist niches survive—slide rules can still be found as circular bezels on watches for aviators and divers—but most instruments are now collector's pieces.

STEPHEN JOHNSTON

SLOGANS FROM SCIENCE. "Eppure si muove" ("Still it moves"), quipped Pope John Paul II after hobbling to the podium on a new hip. He was quoting Galileo Galilei, who is said to have muttered the words after repudiating the Copernican theory under the persuasive pressure of the Inquisition. "Eppure si muove" is an example of "slogans from science," phrases born in or around science and used widely outside it.

It was a "Eureka moment" when "Newton's apple" struck young Isaac. It caused him to associate the force that drew the apple to the earth with the force that retained the moon in its orbit ("essentia non multiplicanda sine necessitate"). Two decades later, Newton had tied the universe together by gravity, without presuming to know its cause ("hypotheses non fingo"). He did know that God had to intervene now and again to keep the planets going, which God did until Pierre-Simon de Laplace showed that no intervention was necessary ("Sire, je n'ai pas besoin de cette hypothèse"). No wonder France had decided that "la République n'a pas besoin des savants."

Changing topics in a "quantum leap," we observe that although "Cogito ergo sum" may be a good test for the existence of a philosopher, it was fatal for "Buridan's ass." Nature is interested in the "survival of the fittest," not of the smartest. That makes no difference in the long run, however, since despite the vast and constant quantity of energy in the universe ("$E = mc^2$," "$E = h\nu$"), "die Entropie strebt einen Maximum zu"; not even "Maxwell's demon" can save the cosmos from "heat death." Of course, war or pollution may get us first. "Nuclear winter" would be followed by a very "silent spring," which could also be achieved by baking ("greenhouse effect") or grilling ("hole in the ozone layer") the creatures of the earth. Whether "ontogeny recapitulates phylogeny" then would not even be of academic interest. Since "ex nihilo nihil fit," there would be little comfort in knowing that "ex ovo omnia" and that life was a "double helix."

J. L. HEILBRON

SOCIAL RESPONSIBILITY IN SCIENCE requires recognition of the social, political, and cultural context and consequences of scientific activity. These consequences include potential risks to health, safety, and the environment. Social responsibility requires acknowledgement of the fact that the institutions in which scientists work also have agendas that go beyond research for the sake of research (e.g., national laboratories for defense, profit-making corporations). On the epistemological level, social responsibility involves discussion of the extent to which scientists have a privileged view of nature and ought to involve the public in decisions about the direction of research.

Between 1600 and 1750, natural philosophers and other creators or disseminators of natural knowledge did not recognize social responsibility beyond loyalty to the patrons who supported them and to devotion to the topic at hand. The patrons included wealthy individuals from the growing mercantile class like the Medicis of Florence; the state and the church seeking technical advice about draining mines and swamps, canalizing rivers, navigating oceans, mapping lands, managing forests; universities and other higher schools; and academies of science.

Between 1750 and 1920, social responsibility evolved in concert with Enlightenment thought and the expanding institutional bases of science. The Enlightenment recommended the study of nature for the advancement of human well-being. The philosophes' engine, the *Encyclopédie* of Denis Diderot and Jean d'Alembert, indicated the responsibility of savants—men of science—to rationalize arts and manufactures. On the eve of World War I, this Enlightenment tradition came together with strong scientific institutions developed in and around the universities. In public health, scientists conducted epidemiological studies, built hospitals, and planned water works and sewer systems to fight epidemics in burgeoning cities. In agriculture, they organized experimental plots and sought new hybrids, fertilizers, and methods of pest control. In the forest and along bodies of water they studied how to manage resources "scientifically" to ensure their availability for present and future generations.

After the war, scientists publicly recognized their responsibility to society. The process centralized in professional societies founded in the late nineteenth century to lobby the government to secure the privileges of recognition, licenses, and financial reward in exchange for service to the greater interests of society. Participation in the war was such a service but an equivocal one. The improvement of the means of destruction, especially chemical weapons, prompted a reevaluation of the potential human costs of research.

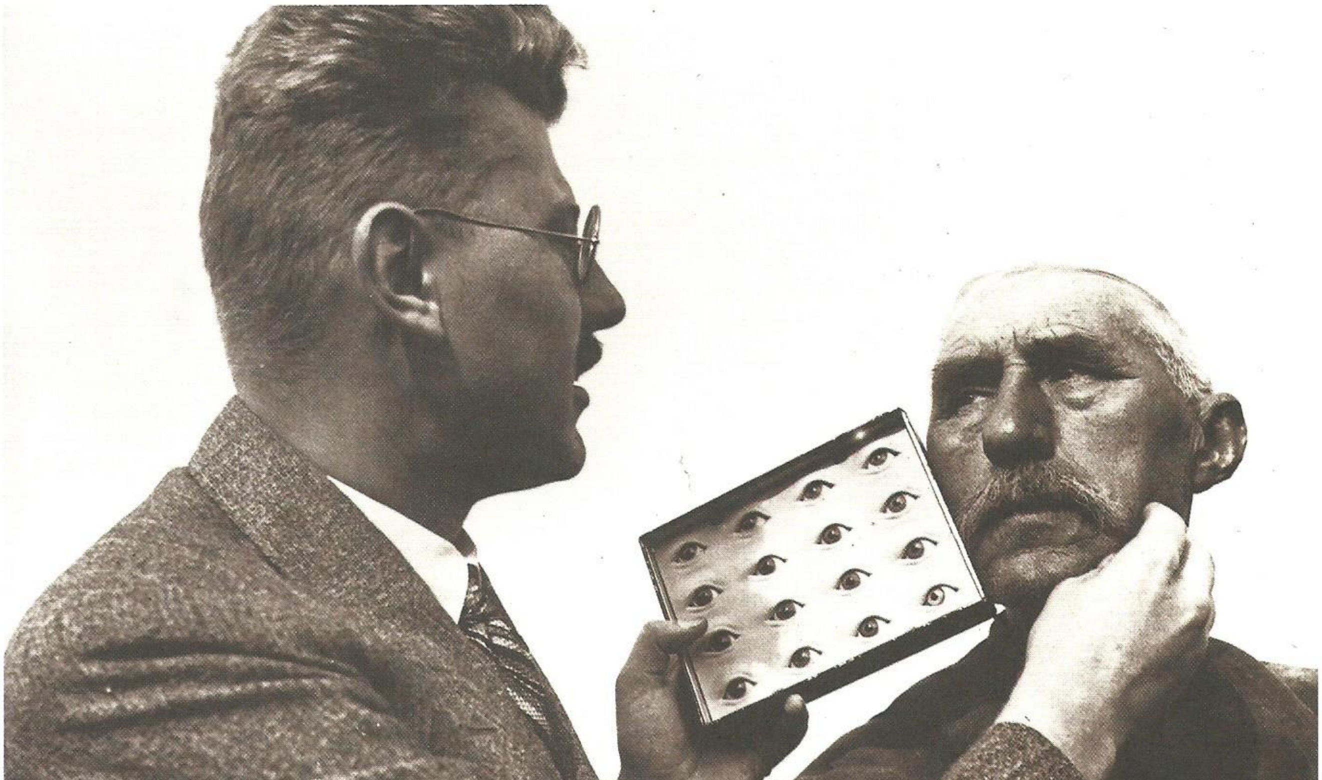
The economic depression of the 1930s, together with the claims of the leaders of the Soviet Union that its scientists served the interests of the masses, rather than the profit motive and the capitalist, contributed to debate about the moral and social compass of scientists. Scientists like John Desmond Bernal in his book *The Social Function of Science* (1939) asked about the impact of science on society, its role in warfare, employment, and social forecasting. The American and the British Associations for the Advancement of Science set up special sections to air these questions.

Three major arenas of scientific activity after World War II forced scientists to engage the notion of responsibility more intimately. The first concerned arms control and disarmament. In the late 1930s, physicist Leo Szilard, with the hope of slowing weapons development, urged his counterparts throughout the world not to publish nuclear research. Early in 1945 scientists in the Metallurgical Laboratory in Chicago issued the so-called Franck Report (named after the chairman of the committee that produced this memorandum, James Franck), recommending all steps possible to avoid the use of nuclear devices. In the postwar years, a large number of scientific groups condemned these new weapons as immoral. They called for a moratorium on their development, outlawing of their use, international control of materials, and sharing of knowledge. Those who spoke out against nuclear weapons included the Federation of American Scientists, the One-World-Or-None movement, and such prominent figures as Niels Bohr, Albert Einstein, and Bertrand Russell. These three and several others established the Pugwash organization, named after Pugwash, Nova Scotia, where scientists from around the world first met in 1957 to pursue verifiable arms control agreements. On behalf of Pugwash, Joseph Rotblat received the Nobel Peace Price in 1995; another arms control organization, Physicians for Social Responsibility, received the Nobel Peace Prize in 1985.

The second arena raising new questions of social responsibility concerned eugenics, medicine, and other biological sciences. Eugenics, the effort to improve the hereditary quality of society, was a mainstream science. But its notorious manifestations, ranging from antimiscegenation policies and laws that barred the "unfit" from reproducing to the sterilization of tens of thousands of allegedly feeble-minded people throughout the world, and especially the horrors of National Socialist "racial hygiene," led the vast majority of scientists to decry biologically determinist arguments. The extreme determinist argument—humans are entirely the product of their genetic material, and programs to improve their circumstances are futile—reached its obscene logical endpoint in the Nazis' Final Solution and horrific experimentation on humans. Another grotesque violation of the sanctity of human life was the so-called Tuskegee experiment initiated during the 1930s. The U.S. Public Health Service observed the path of secondary and tertiary syphilis in four hundred black American males while providing no therapeutic treatment. Although a lead editorial in the *Journal of the American Medical Association* (*JAMA*) condemned the Nazi research in 1948 as totally without merit and morally bankrupt, the Tuskegee experiment continued for nearly forty years. Meanwhile the U.S. Atomic Energy Commission conducted experiments on unwitting subjects in prisons and on Army recruits. An editorial in *JAMA* in 1965 that promulgated a strict definition of informed consent forced many scientists to reconsider their obligations to society. Proper consent took precedence over data generation. This shift in values evolved into institutional commitments such as research advisory committees in government, medical centers, and universities to consider potential risks before the initiation of biomedical research. By the 1990s, the Ethical, Legal and Social Implications program of the Human Genome Project incorporated the commitment to social responsibility directly in genomic research. Some scientists understood that if they did not regulate research activities from within their disciplines, public officials, responding to public concerns, might impose standards that scientists would find too restrictive.

The third major arena for issues of social responsibility concerned the research and production of new pesticides, herbicides, and fertilizers (much of which grew out of chemical weapons efforts) and the well-intended but too frequently disastrous attempts to produce new drugs and food additives, illustrated by the thalidomide birth defects of the late 1950s and early 1960s. Increasing evidence that overuse of chemicals had significant environmental and public health consequences contributed to stricter controls on the development of various chemical products and gave rise to the environmental movement in which many scientists took part.

In many countries of the postwar world, scientists' notion of their social responsibility also came to include obligations to the state in the name of the public welfare, national security, and international prestige that often superceded notions of human welfare. Many scientists have justified research as "science for its own sake," claiming that scientific activity is apolitical (even, and perhaps especially, when it is defined as patriotic). Scientists who embraced internationalist notions of human welfare frequently came under pressure to conform to national norms. In France, for example, Frédéric Joliot became the first high commissioner for atomic energy



Comparison of eye shapes and colors to determine ethnic characteristics at the Institute for Anthropology of the University of Kiel, Germany and directed the construction of the first French atomic pile. Yet he was relieved of his duties in 1950 because of his communist leanings. Scientists and politicians feared he might interfere with national programs to develop nuclear power.

In the Soviet Union, the notion of social responsibility was tied directly to state programs for economic growth and the production of nuclear weapons. Scientists who embraced a Western view of responsibility, such as Andrei Sakharov, and who attempted to advance the notions of academic freedom, the right of contact with foreigners, and human rights issues, usually were demoted or lost their positions. Sakharov and many others were exiled or sentenced to terms in psychiatric hospitals or labor camps.

In Germany, scientists who had been connected with the Nazi war effort—in V-2 rockets, the atomic bomb, or cruel "medical" research conducted at concentration camps—were either "denazified" or co-opted by the new governments. Denazification penalties were determined on the basis of the severity of the activities committed, the date of entry into the Nazi Party, and functions held in both state and party during the National Socialist period. In some cases, this meant prison or loss of job. But many Nazi scientists claimed they had been coerced into research and bore no responsibility for their actions. Many others were useful to German (East and West), Soviet, and American bomb and rocket programs, and willingly declared allegiance to their new states. As a result, denazification was ineffective and inconsistent, and many Nazis who were considered "rehabilitated" never addressed publicly notions of social responsibility. By the 1970s, these forces had generated significant discussion among many scientists about the need to engage society—the public, government officials, corporate leaders, university and laboratory personnel—in considering the potential risks of unregulated research and development. These scientists and engineers sought to encourage a culture in which scientists need not fear reprisals, reassignment, or dismissal for raising concerns over risky science and technology. They were involved in the creation of public interest science groups and the formation of national and international organizations to spread the cause of social responsibility. These include environmental and consumer product organizations.

PAUL R. JOSEPHSON

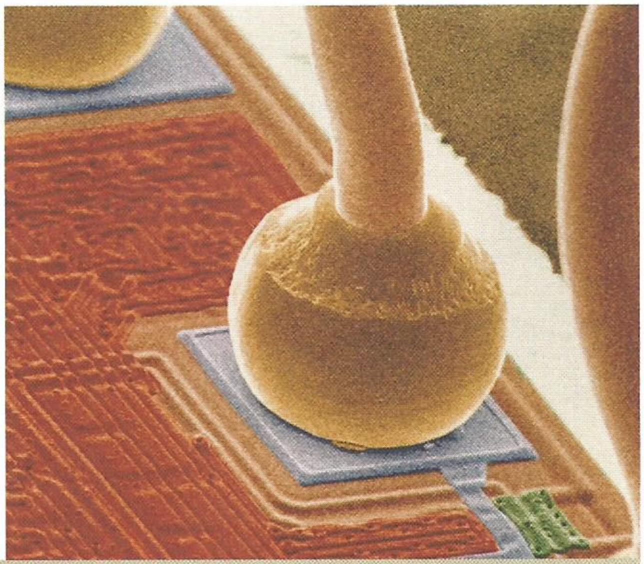
SOLAR PHYSICS. As with many topics in the history of astronomy, solar physics started with Isaac Newton and his *Principia mathematica* (1687). Using his new theory of gravity, the contemporary values for both the Earth-Sun and Earth-Moon distances, and the length of the year and the month, Newton calculated the Sun/Earth mass ratio. Because the Earth-Sun distance was inaccurate, Newton obtained a mass ratio that was eight times too small. By the time of the second edition of *Principia* (1715), however, a better value for the Earth-Sun distance gave the astonishing result that the Sun was about 330,000 times more massive than the earth, and 110 times larger. Doubts about why the earth should orbit the Sun and not vice versa evaporated.

Newton also concerned himself with the source of the solar energy. In his *Opticks* (1704), he often treated the "rays" of light as corpuscular. On this view, the Sun, in emitting light, lost mass. If the loss were not made good, the Sun should dwindle. For Newton, the great comet of 1680 came to the rescue. He calculated that it had passed within 250,000 km of the solar surface. Newton suggested that comets that came closer would fall into the Sun and thus provide it with new fuel and light.

Image of a solar flare or prominence erupting from the chromosphere (colored orange), which lies above the sun's visible surface. The image was taken by Skylab 1.

Worries about the solar energy source resurfaced in the nineteenth century with the realization that the earth, and thus the Sun, had to be much older than the 6,000 years allowed by Bishop Ussher, who in the seventeenth century had calculated from Biblical chronology that creation had occurred in the last week of October 4004 B.C. Measurements by Claude-Sevais-Mathias Pouillet in 1837 of the flux of radiation passing the earth indicated that the sun had a luminosity of about 3.8×10^{26} watts. The suggestion that the sun compensated for this continuous energy loss by accreting meteorites was discarded on the realization that a mass equivalent to about 86 percent the mass of the Moon would have to hit the Sun each year, a gain that results in an unobserved annual increase in the length of the year of 1.5 seconds. In 1854, Hermann von Helmholtz suggested that the sun was contracting and thus converting potential energy into radiated energy. Even though the required rate amounted to only 91 m per year, the accumulated reduction of the Sun's diameter of 50 percent over 5 million years was regarded as untenable. The discovery of radioactivity in 1895 opened the possibility of another source of solar heating. The solution to the problem came closer with Albert Einstein's deduction of the energy equivalent of mass. The direct conversion of solar mass into energy became more plausible in the early 1920s when mass spectroscopy disclosed that four hydrogen atoms outweighed one helium atom. In the mid-1920s, spectroscopic analysis by Cecilia Payne-Gaposkin indicated that about 75 percent of the solar mass was in the form of hydrogen. Astrophysical modeling of the solar interior by Sir Arthur Eddington made the Sun gaseous throughout, and fixed the central temperature high enough, at 15 million degrees, for collisions between nuclei to lead to fusion and energy release. The physicist Hans Bethe worked out the nuclear chemical equations governing the conversion of hydrogen into helium in 1939. It became clear that the sun could produce energy at its present rate for a further 5,000 million years.

The relationship between solar astronomy and physics also appears in the problem of surface temperature. The sun's radiant power was known, but not its law of cooling.



Micro-wires bonded onto a silicon chip as seen by a scanning electron microscope

Father Pietro Angeli Secchi assumed Newton's exponential formula for cooling held, and calculated in 1861 a surface temperature of 10,000,000° K. At the same time, J. M. H. E. Vicaire used the empirical power law proposed by Pierre Louis Dulong and Alexis Thérèse Petit and obtained a value of 1750° K. The introduction of Stephan's law (bodies radiate as the fourth power of their temperature) in 1879 and Wien's law in 1896 pointed to 5,770° K.

Pieter Zeeman's observation of the splitting of sunspot spectral lines enabled George Ellery Hale to measure the magnetic fields in these temporary refrigerated dark regions on the surface (1910). These fields change polarity every cycle, indicating that solar activity varied with a period of around 22 years. Harold D. Babcock and his son Horace W. Babcock used a magnetograph in the late 1940s to show how the magnetic fields of sunspots related to the general solar magnetic field. By the 1960s, the Babcocks had linked the 11-year sunspot cycle, the 22-year magnetic cycles, the magnitude of the general solar magnetic field, and the way in which the solar spin-rate varied with latitude.

Solar flares in the vicinity of bipolar spot groups lead to the ejection of clouds of plasma from the overlaying solar corona. Richard C. Carrington and Edward Sabine in the mid-nineteenth century had related the occurrences of these solar phenomena to the observations of aurorae and geomagnetic storms on Earth. It takes a day or two for the charged particles to travel between the Sun and the earth. Eugene N. Parker put forward a hydrodynamical model that explained how the continuously expanding high-temperature corona produces a solar wind that expands past the planets into interstellar space (1958).

Robert B. Leighton's high-precision Doppler spectrometry of 1960 has measured the velocity of the solar surface along the line of sight and has revealed that the whole solar surface oscillates vertically. Analysis of the modes of this oscillation allow astrophysicists to determine the conditions inside the sun.

David W. Hughes

SOLID STATE (CONDENSED MATTER) PHYSICS. The publisher's note of Galileo's last work, *Dialogues Concerning the Two New Sciences* (1638), informs the reader that the author considered "the resistance which solid bodies offer to fracture by external forces a subject of great utility, especially in the sciences and mechanical arts, and one also abounding in properties and theorems not hitherto observed." By the 1660s, Robert Hooke had discovered the proportionality of stress and strain. Notwithstanding the amazing volume of empirical data amassed by engineers and craftsmen up to the mid-seventeenth century concerning the elastic properties of materials, only in Galileo's and Hooke's work did characteristic features of what came to be known as solid state physics surface: specific assumptions to simplify calculations, which, nevertheless, express underlying physical processes and mechanisms, together with the introduction of "constants" specific to each substance.

Jakob Bernoulli initiated the mathematical study of elasticity, which his nephew Daniel Bernoulli and Leonhard Euler developed in the eighteenth century. By the middle of the nineteenth century the systematic experimental and theoretical investigations of these and other phenomena of the solid state were closely associated with engineering. Slowly the study of solids independently of the problems encountered in their practical use led to the establishment of the first laboratories devoted to work in solid state physics. The main areas of study have been elasticity, crystal structure, strength of materials, thermal and electrical conductivity in metals, thermoelectricity, optical, magnetic, and electric properties of solids, the Hall effect, low and high temperature superconductivity, incandescent lamps, semiconductors, transistors, and computer chips. The amazingly successful explanations of these phenomena rested on general theories such as electrodynamics and quantum mechanics and many new specific concepts. The development of calibration instruments, the needs for standardization, the extensive use of X-ray diffraction, and the attainment of temperatures close to absolute zero helped further to consolidate the study of solids. The discovery of the electron in 1897, the establishment of quantum theory, and, most importantly, the advent of quantum physics in 1926 provided the framework encompassing almost all of the phenomena of condensed matter physics, as solid state physics was called at the end of the twentieth century.

In 1827, Augustin-Louis Cauchy considered solids as continua and proposed a theory of elasticity involving the use of a large number of disposable parameters that could not readily be determined by experiment. The study of crystals brought about a significant change in the treatment of solids. Louis Pasteur discovered in 1848 that tartaric acid can have two distinct crystal forms, each polarizing in a different direction. He inferred that crystals acted as an aggregate of "unit cells" rather than of atoms. The shift from a strict atomic viewpoint facilitated the introduction of symmetry techniques and the understanding of a number of properties as deviations from symmetry.

In 1900, Paul Drude, using the methods of the kinetic theory of gases, showed that the quotient of thermal conductivity and electrical conductivity was proportional to the absolute temperature. This derivation of the empirical Wiedemann-Franz law rested on the assumption that the conduction electrons in a metal could be considered as a free gas. Hendrik Antoon Lorentz proceeded to refine the calculations of Drude by taking into consideration the statistical distribution of the electron velocities and their collision with what he considered to be positively charged atomic cores. His results, which differed from Drude's by a factor of 1/2, also explained other properties such as normal and anomalous dispersion of light, rotation of polarization, and the Zeeman effect.

The experimentally determined dependence of specific heats on temperature at low temperature could not be understood with the model of the free electron gas in solids. It appeared necessary either arbitrarily to reject the gas equation for free electrons or to make the number of free electrons much smaller than the number of atoms in the metals. By 1905, Walther Nernst formulated his heat theorem and surmised that as temperature goes to absolute zero, the specific heat of a body must approach a limiting value independent of the nature of the body. Experimental corroboration in 1910 of the behavior predicted by Nernst helped to consolidate Albert Einstein's treatment in 1907 of specific heats using Max Planck's radiation law.

Undoubtedly the most decisive developments concerning solid state physics resulted from the advent of quantum mechanics in 1926. The electrical conductivity of metals, paramagnetism, diamagnetism, ferromagnetism, magnetoresistance, the Hall effect, the behavior of semiconductors, and superconductivity found a satisfactory explanation within the framework of quantum mechanics. Theoretical solid state physicists faced two particularly vexing problems in their attempts to solve the wave equation in a periodic crystalline potential: the numerical solution of the Schrödinger equation for the problem and the establishment of the proper expression for the potential used in the equation, which involved approximating interelectron effects.

Long before the extensive use of digital computers, physicists developed effective numerical solutions. They handled interelectron effects by likening a solid to a periodic array of associated nuclei and their core electrons immersed in a sea of valence or conduction electrons. The treatment of conduction electrons in solids as nearly free particles occupying a series of energy bands that correspond to the electronic shells of atoms turned out to be so successful that the success itself required an explanation. Why did the electrostatic interactions among the electrons not restrict their freedom? Lev Landau showed in 1950 that a system of strongly interacting fermions (particles that, like the electron, have half-integral spin) can be regarded as a collection of "quasiparticles" resembling free fermions. This idea underlay the development of the excitation model of the solid that formally solved the puzzle of how supposedly highly correlated electrons can act as if free.

The understanding of the magnetic properties of matter remained elusive for a long time. Empirical methods and a mass of data about magnets provided sufficient information for the construction and manipulation of magnetic and magnetized materials. By 1903, Joseph John Thomson had come to consider magnetism as a property of atoms and to attribute both paramagnetism and diamagnetism to the motion of the atomic electrons under their reciprocal repulsions and the externally applied field. Pierre Curie's systematic experimental treatment of magnets and his empirical law that the magnetization of a paramagnetic body is proportional to the intensity of the magnetic field divided by the absolute temperature became the background for Paul Langevin's theory of 1905. This theory, based on ideas of Thomson and Lorentz's electrodynamics, derived para- and diamagnetism from magnetic moments arising from motion of the atomic electrons. In the late 1920s, Werner Heisenberg showed that the exchange interaction between electrons might be the key to an understanding of the success of Langevin's approach.

In 1926, Wolfgang Pauli calculated the paramagnetic susceptibility quantum mechanically on the assumption that an electron gas consists of free fermions. In contrast to the prediction of the classical treatment, Pauli found that at low temperatures the susceptibility approached a constant. Only electrons in metals within a certain small range of energy can be aligned by the magnetic field, an effect that dramatically decreases the magnetic susceptibility in metals.

The electron theory of metals was systematically developed after 1928, the year that Felix Bloch defended his doctoral dissertation under Heisenberg at the University of Leipzig. Bloch assumed that the electrons did not act on one another and that they moved freely through a lattice (the metal). A perfect lattice of identical atoms would give an infinite conductivity; electrical resistance resulted from lattice imperfections or ionic motion. Bloch also proved that if the electron Fermi distribution was in equilibrium and at rest with respect to the lattice, and if it had the same temperature as that which the lattice vibrated, then the electrons and the vibrations would be in equilibrium. In this case the motion of electrons did not have any consequences for the thermal motion in a solid. From these considerations Bloch derived a temperature dependence for electrical resistivity.

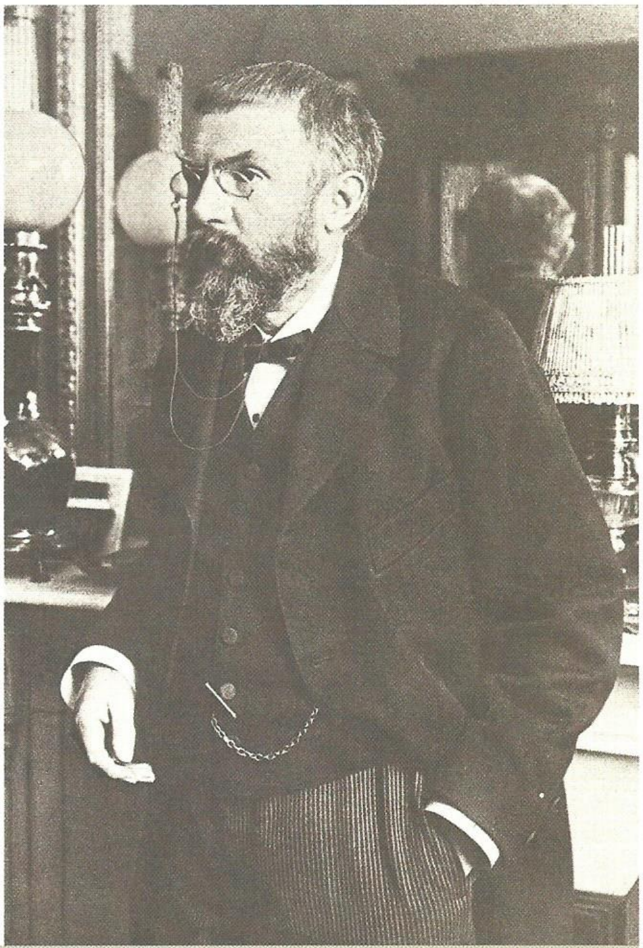
Hans Bethe's doctoral dissertation with Arnold Sommerfeld was another turning point of the electron theory of metals. He showed that electrons with negative potential energy in a metal have a larger kinetic energy inside it than outside, and concluded that the crystal shortened their wavelengths. This explained the positions of the maxima in electron-diffraction experiments, which did not agree with the predictions of the previous theory. Two additional notions associated with Bethe's close friend Rudolph Peierls—holes and band gaps—became important in understanding the conduction processes in metals. In his attempt to deal with the anomalous Hall effect, Peierls found that the Hall constant in the limit of a slightly filled energy band had the same value as that derived by the classical electron theory. In a nearly full band, it again had the value derived by the classical electron theory, but now for carriers of positive charge equal in number to the unfilled states in the band. These vacancies or holes in an otherwise full band behaved as positively charged bodies. Since, as Peierls showed, electrical conductivity vanished in the case of completely occupied bands, the holes (the negative electrons in Paul Dirac's quantum electrodynamics) became an indispensable notion for understanding the behavior of electrical insulators.

In 1934, Eugene Wigner and Frederick Seitz calculated the bands of sodium, a monovalent metal. They modeled the crystal as a network of identical cells surrounding single metallic ions and thus considered the conduction electron in each cell to be influenced only by its "own" ion's field. This calculation initiated other studies of band structures of real materials.

The nearly free electron model could not account for low temperature phenomena such as superconductivity and superfluidity or for phase transitions and critical (or collective) phenomena. Here interactions between the electrons became important. Not until after Wold War II, however, were the necessary many-body methods developed. New concepts like elementary excitations (phonons, spin waves, quasi-particles), macroscopic wave functions (long range order), order parameters and changes of symmetry in phase transitions, collective modes, low-lying excitations above the ground state, Bose-Einstein condensation, pairing, and broken symmetries played an important role in understanding these interactions. The articulation of the notion of macroscopic quantum effects, first formulated by Fritz London in 1936, brought about a deeper understanding of these phenomena.

Electronic conductivity of semiconductors and the mechanical properties of metals are controlled by minute additives of foreign atoms or by irregularities in crystalline structure. Small concentrations of defects in a largely undisturbed lattice have strong effects on macroscopic crystal phenomena such as optical properties and electrical conduction. Semiconductors (flawed crystals) became a separate class of materials and the objects of intensive research, much of it done in industrial laboratories. In one of the largest of them, Bell Laboratories in the United States, researchers invented the transistor. The contact of two crystals, one with a minute excess of electrons and the other with a predominance of holes, formed the so-called p-n junction, the basis of the transistor. The need for purer materials, the understanding of structure-dependent properties, and the introduction of specific impurities defined the possibilities of semiconductors, and led to the elucidation of their most important property, the rectifying contact that made the transistor practicable. Lasers soon followed.

Research and development in many universities and industrial research laboratories, the direct and intense interest of the military, and the profitability of the new materials and inventions based on the understanding of the many properties of the solids played a decisive role in shaping the characteristics of solid state physics. These characteristics derived from many schools of thought and experimental practices from all over the world.



Henri Poincaré (1854–1912), French mathematician and mathematical physicist, who made important contributions to the theory of relativity

The only person to have been awarded the Nobel Prize twice for the same science was John Bardeen, who shared the physics prize for his work on semiconductors and again for his work on superconductivity, in 1956 and 1972, respectively. This unique honor reflects solid state physics' idiosyncratic inheritance of diverse phenomena, intriguing problems, and miscellaneous methods.

Kostas Gavroglu

SPACE AND TIME. The evolution of the modern understanding of space and time, which is closely related to the formation and development of physical sciences, can be divided into three stages dominated by Newton's absolute space and time, Minkowski's spacetime, and Einstein's spatial and temporal structures constituted by gravitational fields interacting with material bodies or other physical fields.

Absolutism

The scientific revolutionaries of the seventeenth century rejected the scholastic view of space and time as accidents of substance along with most other fundamental tenets of Aristotelianism. Against this view, which left no room for a void and assumed that time was the same everywhere at once, the revolutionaries flirted with atomism and other systems that gave space an independent existence.

Here, René Descartes took an intermediate position. Although he rejected the notion of space as an immaterial, infinite, immobile container with indistinguishable parts, he did allow it an independent, even a material, existence, by characterizing it by its extension and identifying it with matter. He thus rejected a vacuum in favor of a plenum, and deduced that motion can be transmitted only by impact, that motion of a body can be measured only relative to other bodies, and that the total motion in the universe is conserved. Conservation of motion suggested to him a principle of inertia, according to which uniform rectilinear motion is equivalent to rest, but rest requires for its definition an immobile frame of reference, which, alas, cannot be supposed within the ceaselessly moving Cartesian universe.

In forming his theory of motion, Isaac Newton recognized the importance of Descartes's principle of inertia, transformed it radically, and provided it with new conceptual foundations. By conceiving the inertia of a body not as an expression of the conservation of its motion, but as its inertness measured as its mass, Newton purchased ground for taking force, an external mover of inert matter, as a primitive entity existing independently of bodies. To give meaning to the revised notion of inertia and to make the revised law of inertia self-consistent, Newton promoted the atomists' void into a primitive entity.

If motion occurs only relatively to other bodies, immaterial and immobile space as a frame of reference is dispensable; but if absolute motion exists, then the frame of reference has to be taken as a primitive concept (absolute space). Newton adduced the motion of water in a rotating vessel as evidence of a centrifugal force generated by a rotation in absolute space. He described this space eloquently as an entity that, in its own nature, without relation to anything external, remains always similar and immovable. In the same manner, without much argument, Newton defined true time as absolute time, which, of itself and from its own nature, flows equably without relation to anything external. He understood absolute space and absolute time as attributes of God, one expressing divine omnipresence, the other divine eternity.

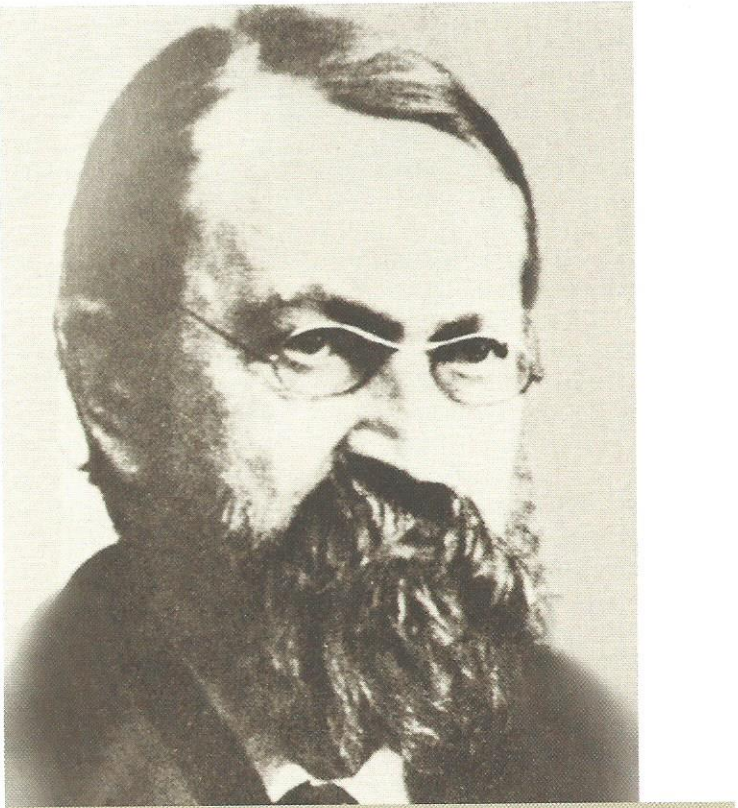
Newton's absolutist view of space and time came under criticism from Christiaan Huygens and Gottfried Leibniz. Huygens tried to interpret rotation as a relative motion of the parts of the rotating body, driven to different sides and in different directions, and argued that this relative motion gave the appearance of centrifugal force in Newton's bucket experiment. But this argument failed because in a rotating coordinate system, parts rest but the centrifugal force does not disappear. Leibniz employed his principles of the identity of indiscernibles and sufficient reason to dismiss Newton's absolute spatial and temporal relations and to insist, characteristically, that in Newton's homogeneous absolute space, God would have had no reason to create the world in the way he did rather than in infinitely many other ways. But since Leibniz had to accept rotation as an example of absolute motion, and offered no relational theory to accommodate it, his metaphysical arguments did not carry much force for his contemporaries.

In the two centuries after Newton, natural philosophers accepted absolute space and time as the bedrock of physical theory. The only significant challenge came from Immanuel Kant. In his influential teaching, space and time are imposed by us on the world as the ground or possibility of our intuitions of it. Kant's *a priori* view of space collapsed with the discovery of non-Euclidean geometry in the mid-nineteenth century. But his transcendental arguments about space and time as necessary prerequisites for experience was revived by Niels Bohr and many others concerned to anchor quantum physics on classical observables in space and time.

Spacetime

Newton defined absolute space in terms of the resting center of gravity of the world. However, for the validity of mechanics, any "inertial system," that is, any body moving uniformly with respect to absolute space, could serve as a reference system. The question of inertial systems in mechanics was entangled with the question of the ether, the carrier of electromagnetic waves, in the late nineteenth century. Since physicists tended to identify the ether with absolute space, they expected to be able to detect the effect of motion relative to it. The negative result of the Michelson-Morley experiment (1887) posed a puzzle, explained away by the hypothesis, suggested by George Francis FitzGerald and Hendrik Antoon Lorentz, that moving bodies, owing to their interactions with the ether, contract along their line of motion. Lorentz's explanation (1895, 1902), also proposed by Joseph Larmor in 1900, made use of a quantity they called "local time," different for different observers, which they regarded as a mathematical artifice. When local time was taken to be the real time for a moving observer, first by Henri Poincaré in 1902 and then by Albert Einstein in 1905, the absolutist notion of a single universal time collapsed, and absolute simultaneity could no longer be defined. Times and locations can be defined meaningfully only in accordance with the states of motion of inertial systems. The relation between the space and time coordinates in two inertial systems in relative motion can be obtained mathematically from the principle of relativity (physical laws take the same form in all inertial systems) and the postulate of the constancy of the speed of light, first suggested by Poincaré in 1902, without resorting to the contraction hypothesis.

In 1905, Poincaré noted that the mathematics (Lorentz transformations) that relate spatial and temporal intervals of inertial systems to another mixed spatial and temporal coordinates, but left the formula for the spacetime intervals between events the same in all coordinate systems. Poincaré observed further that this formula behaved as if it represented a four-dimensional analogue of a line in three-dimensional space, so that the Lorentz transformations could be pictured as four-dimensional analogues of ordinary rotations. These observations suggested a complete change in the ideas of space and time to Hermann Minkowski. He conceived the relative spaces and times of inertial systems as projections of an absolute four-dimensional spacetime manifold, the true and independent stage for physical events to occur, onto the three-dimensional space of the observer.



The Austrian physicist Ernst Mach (1838–1916) influenced the creation of the quantum theory (via Planck) and relativity (via Einstein) through his philosophy of science and ideas about space, mass, and measurement.

Absolute spacetime has richer structures than absolute space had. Most important among them is the light cone, defined at each point by the events that can be causally related to the observer and those that lie absolutely elsewhere and absolutely elsewhen. Minkowskian spacetime, together with its kinematic and causal structures, has replaced Newtonian absolute space and time and played a foundational role in all forms of relativistic dynamical theories, including quantum mechanics and quantum field theories, except for the general theory of relativity and its variations.

Dynamical Spatial and Temporal Structures

Non-Euclidean geometries make possible use of intrinsic local variations of curvature to designate positions in space without resorting to a material coordinate system and thus opened the way to a new version of absolute space. But Bernhard Riemann observed in 1854 that since the structure of physical space had to be determined by physical forces, the new notion of absolute space could not be sustained. Einstein vigorously pursued Riemann's idea in developing his general theory of relativity. Here Einstein's work shows the influence of Ernst Mach, whose program of freeing science from metaphysics included ridding the world of the concept of absolute space. In 1883, he rejected Newton's crucial bucket experiment with the argument that the centrifugal forces on the water arose because of its relative motion with respect to the mass of the earth and the other celestial bodies. Mach thus replaced absolute space with the cosmic distribution of matter, which would determine the inertia of bodies and the spatial structures of local inertial systems, and thus provide dynamics with a relationist foundation.

Einstein's general relativity (1915) has a spatial structure (curvature or metric) that varies with the distribution of matter. But an interpretation of general relativity along Mach's lines ran into trouble with the discovery of the "vacuum solution" to the theory's equations, which showed that spatial structures exist in the absence of matter. Further reflection showed that any description of the properties and state of matter necessarily involves a metric as an indispensable ingredient, and thus presupposes the existence of spatial structure. Thus, although Einstein initially liked Mach's idea, which, in 1918, he raised to "Mach's Principle," he later (1953) rejected it. In his final formulation, dynamical (gravitational or metric) fields, but not masses, determined the spatiotemporal structures that grounded the dynamic behavior of everything in the world. Spacetime as a quality of the field had no independent existence.

There seems to be unanimity that spatiotemporal structures are not conventional, but specified or constituted by metric fields or their variations. Serious disagreements nevertheless persist over the ontological status of spacetime. Substantivalists ascribe spatial-temporal positions and structures directly to the individual points of a spacetime manifold, and only in a derivative sense to physical entities occupying points of the manifold; relationists claim that the spacetime characteristics of a physical entity belong to it in a primary and underived sense.

Some ardent substantivalists argue that an immovable spacetime substratum as a primitive existence has to be presumed if we wish to ground absolute motions and field theories. The relationist counters that absolute motions can be measured by deviations from geodesic motions and that chirality (right- or left-handedness), as Kant had realized, cannot be understood by reference to the points in absolute space. It is an intrinsic spacetime characteristic of physical entities and belongs to them in a primary sense.

TIAN YU CAO

SPACE SCIENCE. The term "space science" came into use in the late 1950s just after the Soviet Union launched *Sputnik I,* but it had antecedents in the 1930s, when astronomers climbed mountains to observe the heavens and meteorologists and physicists sent instruments aboard highflying balloons to study cosmic rays.

After World War II, captured German V-2 missiles and their immediate successors, like the Navy's *Viking* or the long line of Soviet missiles based upon V-2 technology, carried probes into near space to examine Earth's upper atmosphere, the nature of cosmic rays, the Sun's high-energy spectrum, and the particles and fields contained within Earth's magnetic system. After *Sputnik,* space science research relied on rockets powerful enough to send nuclear warheads ballistically to another continent or satellites into orbit. Space science identified its programs in terms of the capabilities of specific transport vehicles—balloons, aircraft, sounding rockets, satellites, and space probes.

In Britain, most of the activity in the 1950s centered on the Gassiot Committee of the Royal Society and on less formal splinter groups at major university centers. The society's members had established interests in the physics of the upper atmosphere and had followed closely the progress of the rocketry groups in the United States. Starting in 1955, they championed what became known as the *Skylark,* a sounding rocket on the scale of the American *Aerobee,* and eventually gained access to space post-Sputnik with the Ariel series of scientific satellites sent up by American vehicles. Meanwhile other British launchers were being developed—*Blue Streak* (based on preexisting military systems) and *Black Knight* (developed out of research programs)—but they did not survive as scientific launchers once Britain decided to work within an international structure.

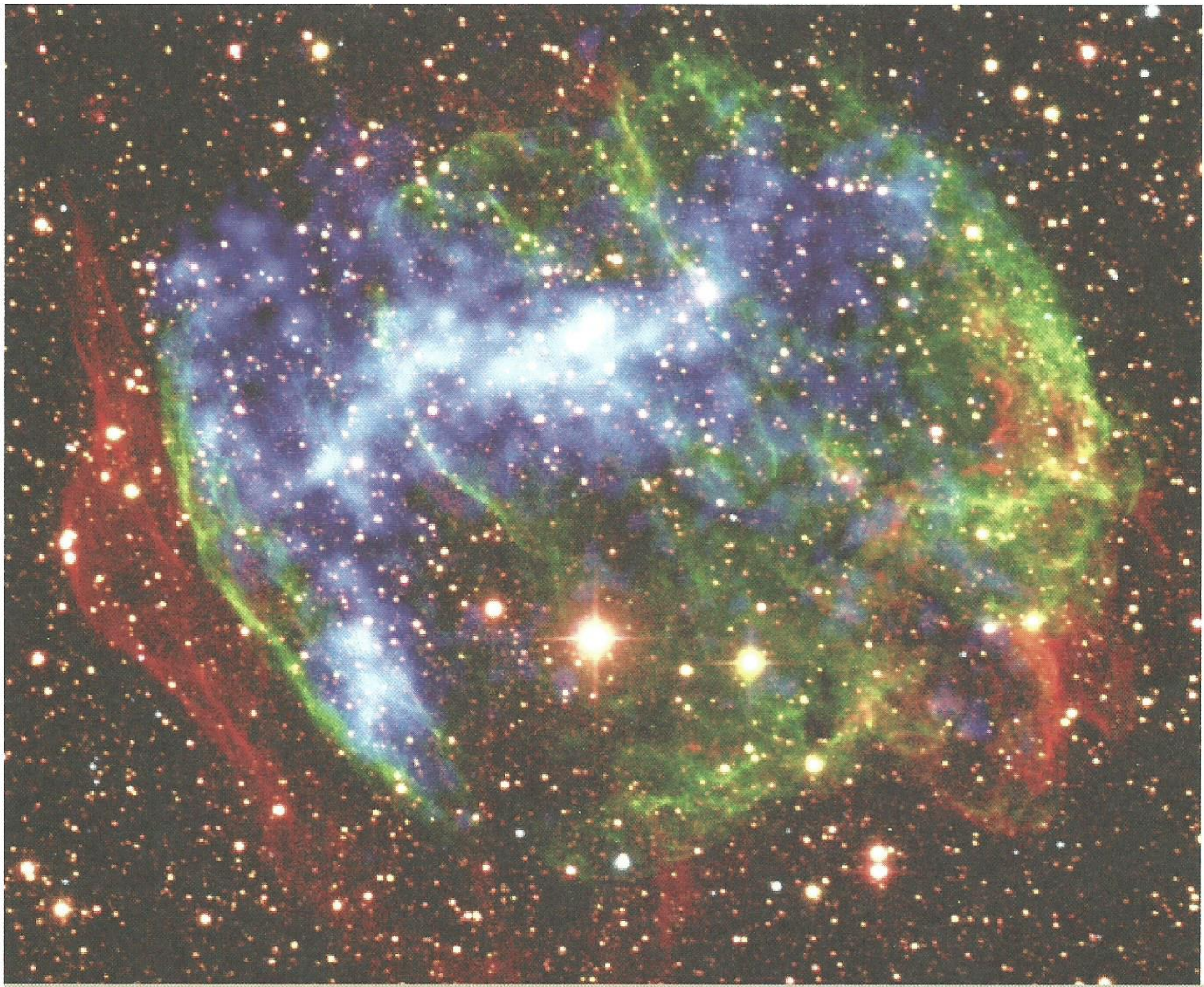
In the United States, those who instrumented the V-2s between 1946 and 1951 came from disciplines that traditionally had not inquired into the natural phenomena they now addressed with rockets. They were practical, tool-making, problem-solving physicists and engineers experienced in building and maintaining long-range radio networks, rugged and reliable high-speed optical systems, proximity fuses for artillery shells, and radiation detectors for atomic tests. These were the skills needed to make an instrument perform delicate observations in the violently hostile realm of the rocket.

A second generation of practitioners, typically trained in the university groups that had access to rockets in the 1950s, did postdoctoral work in military laboratories. They tended to identify more with the disciplines they could address with the instruments they built than with the objects of their handiwork. Starting in the 1960s, leading academic scientists like Lyman Spitzer, Jr., at Princeton, Leo Goldberg at Harvard, John Simpson at Chicago, James van Allen at Iowa, Fred Whipple at Harvard, Charles Hard Townes at Berkeley, Joshua Lederberg at Wisconsin, William Dow at Michigan, and Joseph Kaplan at UCLA supported graduate students and assistants on contracts from NASA, the Air Force, and the Navy to develop instruments and techniques to pursue science from space.

Graduate students in astronomy were attracted to groups conducting solar physics from rockets, and became specialists in methods most suited to studying the Sun from space. Many went on to satellite-based research in the 1960s and to manned orbiting platforms in the 1980s and 1990s. As the generational cohorts established stronger and stronger interdisciplinary ties with traditional areas of research, they migrated more freely within their subject matter disciplines; generally they no longer moved from one scientific discipline to another but were attracted to problems within their discipline where they could exploit their expertise with rocket and satellite technologies.

Space science thus came to lie at the intersection of three elements: a technical capability (the use of rockets and satellites as platforms to make observations of any accessible phenomenon) with a scientific interest (framing problems that can be addressed by observations from rockets and satellites) and a military or commercial need (creating a capability to use and manage space for communication, weapon delivery systems, reconnaissance, and command and control). At the intersection, expensive, government-sponsored technologies made research in space possible.

Scientific satellite development roughly followed the growth of the launch capabilities of the vehicles. The very first American scientific satellites, those typical of the long-lived Explorer series, were single-purpose instrument



A composite image of the Chandra X-ray (blue) and Palomar infrared (red and green) observations of the supernova W49B reveals a barrel-shaped nebula consisting of bright infrared rings around intense X-radiation along the barrel's axis.

packages weighing thirty to one hundred pounds. They contained primitive telemetry systems, on-board data storage, and rudimentary temperature stabilization. By the early 1960s, spin-stabilized "observatory" class satellites (the Orbiting Solar and Geophysical Observatories) and the multifunctional but unstabilized Ariel series were flying. These satellite series coexisted throughout the 1960s and offered access to a wide range of electromagnetic phenomena from the Sun, Earth's magnetosphere, and the interplanetary medium. Dedicated sounding rockets and a few experimental high-energy satellites began to detect nonsolar X-ray sources: the first fully dedicated X-ray mapping satellite, *Uhuru,* was launched only in 1970 as the forty-second in the Explorer series.

The first of the OAO series appeared in 1968. With the OAO, in a weight class of thousands rather than hundreds of pounds, lead times crept up during the 1970s from a few to many years and began to slow the pace of training and advancement in the participating disciplines. Astronomers have called OAO-2 the first true observatory in space because the scale and resolution of its instrumentation complemented those available on the ground. It operated from December 1968 to January 1973 and could achieve a pointing accuracy as good as 1 minute of arc with a stability of some seconds of arc providing the capability to secure sustained photometric and spectroscopic data from tiny celestial sources.

In the post-Apollo era, two drivers of the American space program both propelled and severely limited the continuing development of science satellites. The primary driver was NASA's preoccupation with establishing a permanent human presence in space. As the Apollo program wound down in the wake of the successful lunar landings between 1969 and 1972, NASA decided that national goals could best be met in a reusable launch system, the Space Shuttle. Accordingly it concentrated access to space in the Shuttle bay, severely reducing or eliminating altogether suborbital and orbital programs based upon conventional launch vehicles. This had the effect of requiring even the smallest packages to be rated for human space flight, vastly increasing costs and lead times for development and testing.

At the same time, NASA's propensity for mission-based, rather than problem-based, programming drove up the scale of successive satellites. While the OAO's were flying and scientific groups tried to keep alive programs in the Explorer and smaller observatory and planetary probe classes, NASA and a vocal faction within the scientific community set their sights on a "great observatory" class of satellites, instruments that would fill the Shuttle bay and offer truly high resolution and broadband access to the faintest of celestial sources. This older class had been wildly successful beginning in the 1970s. By the end of the century, all the planets save Pluto had been visited, mapped, revisited, and, in the cases of Mars and Venus, investigated by landers. In the 1980s and 1990s, however, the costs of these probes were competing directly with the great observatories like the Hubble Space Telescope, the Compton Gamma Ray Observatory, the Advanced X-Ray Astronomy Observatory (AXAF, renamed *Chandra*), and the Space Infra-Red Telescope Facility (SIRTF). Pressure mounted under competition from satellites of the European Space Agency and Japan.

For these reasons, as well as a lack of public enthusiasm for the continuation of NASA programs at the levels enjoyed in the Apollo era, American promoters of space research increasingly sought out new and more substantial modes of international cooperation at all levels, from Explorer to great observatory class. Few nations have the resources to conduct science from space. The United States from the start entertained an international program, mainly to launch instruments, and in some cases, satellites, for other countries. The Soviet Union soon followed, and all eventually recognized the need for the creation of a new international body, now the Committee on Space Research (COSPAR), that would coordinate international participation in space research. Many countries, including Great Britain, created new organizational structures to communicate with the international body. Thus, COSPAR formed and quickly assumed far broader international responsibilities.

At the same time, the United States announced that it would provide launch vehicles for COSPAR countries as its contribution to international cooperation. Initially western Europe, Great Britain, and the Commonwealth countries dominated COSPAR, with a strong representation from the United States and hardly any from the Soviet Union and Eastern Bloc. This was not satisfactory to member countries of ICSU, and eventually the Soviet Union joined COSPAR, which thus became an important forum for international cooperation, eventually as an agency within the United Nations. Its existence, and the American offer of launch vehicles, weakened British resolve to purchase its own systems. The United States sealed the arrangement when it announced at a meeting of COSPAR in March 1959 that it would provide launch systems without charge.

The emergence of the European Space Research Organization (ESRO), and out of that the European Space Agency (ESA) in the 1960s, even with Britain's initial reluctance to join in, marked the completion of the overall structure for space science in Europe and the Americas. Led by France, ESA produced a competitive launch vehicle, *Ariane,* which prompted creation of similar-scaled vehicles in China and Japan. Thus at the beginning of the twenty-first century there exist five competing national—or, in the case of ESA, transnational—sources for placing satellites into orbit. Before the multinational armada of space probes that met Halley's Comet in the spring of 1986, the United States and Soviet Union were the only countries actively supporting interplanetary probes, landers, and orbiters. By 2000, at least four of the five major launching programs were considering new probes, orbiters, and landers.

David Devorkin

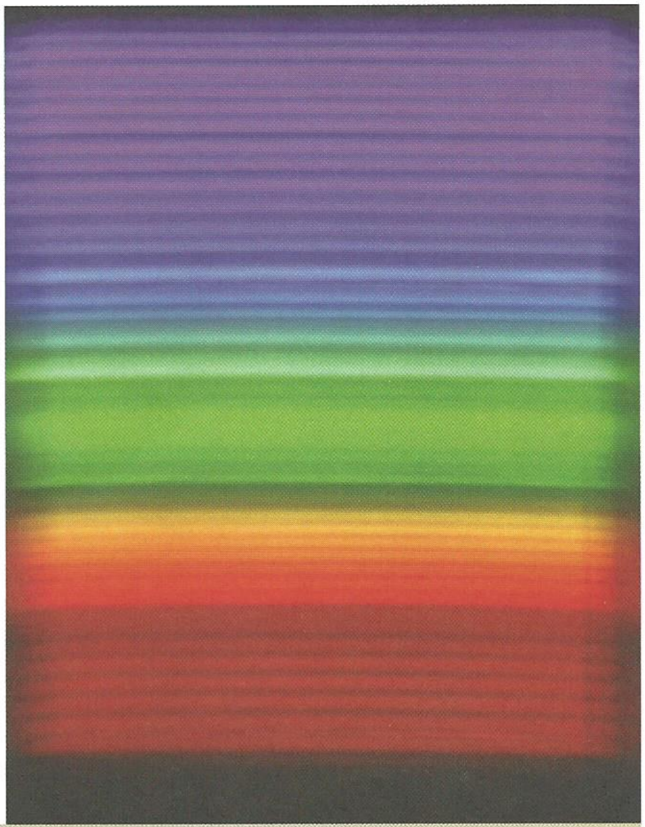
SPECTROSCOPY is the science on the borders of chemistry and physics that studies the properties of matter by analyzing, usually prismatically, the light it emits when rendered incandescent. Spectroscopy's progress has depended on the development of the necessary equipment. It uses physical methods to study chemical phenomena. Not until a chemist and a physicist collaborated in working on spectra did spectroscopy begin to yield useful chemical knowledge.

While working to improve optical glass, Joseph von Fraunhofer found that flame spectra were characterized by discrete bright lines. He also found a number of dark lines crossing the continuous spectrum of the sun and noted that their positions did not change with intensity. These dark lines, subsequently named after him, still bear the letters he used to designate them.

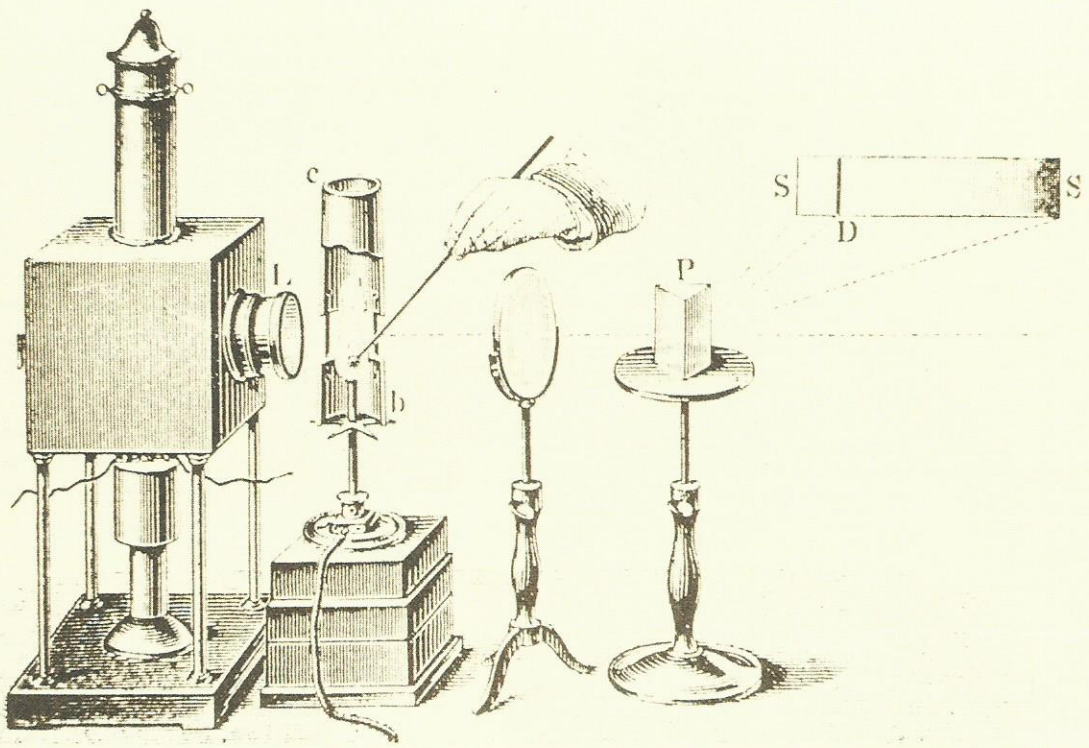
While spectral lines facilitated the calibration of optical instruments, their meaning eluded satisfactory explanation for many years. The physical interpretation of the lines played a major role in the wave-particle debate over the nature of light that raged, especially in Great Britain, during the 1820s and 1830s. William Henry Fox Talbot suggested in 1826 that spectral lines might be used for chemical analysis. This idea, however, was not pursued, largely because the generally poor quality of glass prisms made it difficult to achieve replicable results, as did the impurities present in chemical substances. Attempts in the 1840s and 1850s to analyze the spectra of electric sparks also came to little, although the theory behind them favored the development of spectroscopy.

From his work on photochemistry in the 1850s, Robert Bunsen, professor of chemistry at the University of Heidelberg, became convinced that the light emitted from flames was uniquely characteristic of the chemical elements present. He pursued this idea with the school's professor of physics, Gustav Kirchhoff. Together they showed conclusively, in 1859, that a chemical element emitted a uniquely characteristic spectrum that could be used for chemical analysis.

In 1860–1861, using what was then known as spectrochemical analysis, Bunsen detected and then chemically



The spectrum of a pure element is unique to it. The spectra pictured here belong, from top to bottom, to bromine, deuterium, helium, hydrogen, krypton, mercury, neon, water vapor, and xenon.



Spectroscope dating from around 1900. The illuminated specimen contains sodium, whose prominent D line is indicated in the absorption spectrum beyond the prism at P.

isolated two hitherto unknown chemical elements, cesium and rubidium, which occurred in trace quantities in mineral waters. In 1861, William Crookes in London discovered the chemical element thallium using spectrochemical methods. These discoveries placed the new method on a secure evidential basis. Furthermore, they helped popularize knowledge of the new method and to arouse widespread interest. In 1865, August Wilhelm von Hofmann demonstrated spectroscopy to Queen Victoria at Windsor. Thus publicized, the method quickly became established as an invaluable laboratory technique.

During the same period, Bunsen also collaborated with Kirchhoff to show experimentally that the bright yellow lines characteristic of sodium corresponded with Fraunhofer's dark D lines in the solar spectrum. Kirchhoff provided a thermodynamic explanation of the coincidence. This extension of chemical analysis to the sun and stars (entities that the French philosopher Auguste Comte had pointed to in 1835 as examples of things forever unknowable) led to the new science of astrophysics. In the ensuing decades, spectroscopic observations allowed astronomers to develop theories of the evolutionary sequence of stars. Measurements made in the late 1890s on the spectrum of cavity radiation prompted Max Planck's quantum theory. Somewhat later, using the measurements and analyses of the distribution of lines emitted by particular elements, physicists began to investigate the internal composition of matter, leading to Niels Bohr's theories of atomic structure. The discovery of the diffraction of X rays in 1911 led to high-frequency spectroscopy with crystals rather than glass prisms as analyzers, and to important information about the deeper reaches of atoms.

The obvious benefit of the spectroscope to a wide range of scientific and technical activities prompted its commercial manufacture by a large number of instrument makers throughout Europe. The instrument was refined and developed during the late nineteenth century by substituting diffraction gratings or hollow prisms filled with carbon bisulphide for the glass prism. Some spectroscopes had prisms so arranged that they appeared to resemble telescopes. The basic principles and uses of the spectroscope did not undergo any fundamental change until the invention of the mass spectrograph in 1919.

Frank A. J. L. James

SPONTANEOUS GENERATION. "Spontaneous" or "equivocal" generation denotes the widespread belief in the production without parents and by chance of living beings either from decomposing living matter (heterogenesis) or from nonliving matter (abiogenesis). This belief, which dates back to ancient times, has often taken the form of sophisticated doctrines related either to the generation of specific living beings like insects, infusoria, and bacteria, or to the origin of life itself.

Like the ancients, most authors of the seventeenth century believed that flies sprang from rotting meat. By experiments and microscopic observations Francesco Redi demonstrated that the maggots observed in rotting meat came from eggs laid by flies (*Esperienze intorno alla generazione degl'insetti,* 1668). Jan Swammerdam and Marcello Malpighi, who showed that plant galls also resulted from insect eggs, confirmed Redi's results.

Although the microscopist John Turberville Needham (1713–1781) explicitly rejected the doctrine of equivocal generation, his complex theory of generation by vegetation seemed to most of his contemporaries and successors to support it. He carried out observations on the animalcules arising in infusions and explained their generation as the result of the decomposition of living matter, which released "active" forces able to produce new "vegetations" (*Nouvelles observations microscopiques,* 1750). In 1765, Lazzaro Spallanzani argued against Needham's active forces, proposing instead that the animalcules were true animals

Lazzaro Spallanzani (1729–1799), Italian naturalist

generated from eggs present in the air that contaminated the infusions. By repeating Needham's experiments with sealed and heated infusions, Spallanzani showed that if boiled infusions were placed in previously heated hermetic flasks to destroy all existing eggs, no animalcules would be generated. By contrast, if air entered the flasks animalcules proliferated.

Between 1858 and 1864, a fresh controversy took place in France. Félix-Archimède Pouchet claimed that airborne contamination of infusions was unlikely because he had rarely found spores and living particles in air. Therefore only spontaneous generation could account for the microorganisms found in infusions (*Hétérogénie,* 1859). Stimulated by the debate begun by Puchet, Louis Pasteur filtered air with an instrument of his own making and concluded that air did contain microorganisms and that flasks with sterilized sugared yeast water remained sterile if not contaminated by it.

At the same time that the doctrine of spontaneous generation seemed to have been finally superseded by the postulate that life could only be transmitted by preexisting life, some evolutionists posed the question of the origin of life in general from nonliving matter. New terms were introduced to indicate the passage from ordinary to living matter: "abiogenesis" by Thomas Henry Huxley, "archeobiosis" by Henry Charlton Bastian, and "Urzeugung" (primordial generation) by many German authors. According to August Weismann, spontaneous generation was a logical necessity notwithstanding the failures to demonstrate it. In 1924, the Russian biochemist Aleksandr Oparin argued that life did not arise immediately but slowly emerged from a long-term chemical evolution. His ideas, expressed in many widely circulating books, received near-universal acceptance.

Renato G. Mazzolini

STANDARD MODEL. During the 1980s, physicists who worked on elementary particles came to agree that matter consists of three pairs of leptons—very light and even weightless particles—and their antiparticles (of which electrons and their corresponding neutrinos are the exemplars) and three pairs of quarks and their antiparticles (of which protons, neutrons, and other heavy particles, or "baryons," are made). So much for the bricks. The mortar that holds the quarks together (the "strong force") comes in eight kinds of "gluons"; the cement that binds leptons to one another and to quarks (the "electroweak force") consists of the photon (the electrical part of the force) and three adhesives, W^+, W^-, and Z^0 (the weak part). The detection of the W and Z particles and the top quark in 1982–1983 completed the experimental identification of the elements of the standard model. The successes of this model gave impetus to Grand Unified Theories (GUTs), intended to unify the strong and electroweak forces, and to dreams of Theories of Everything (TOEs).

Some particle physicists, notably Steven Weinberg (who won the Nobel Prize in physics in 1979), have asserted that now that the guts of GUTs are in place, the final TOE will soon follow. A glance at earlier claimants to the status of "standard model" does not give cause for confidence in his prediction. To go back no further than 1800, the system of imponderables developed by Pierre-Simon de Laplace and his school seemed capable of describing all the phenomena then known in the same terms (though not the same language): several leptons (the weightless "fluids" of electricity, magnetism, heat, light, and so on), a baryon (the particles of "common matter"), and forces of attraction and repulsion. Many natural philosophers looked forward to a unified theory that would connect the various "fluids" (leptons), a project encouraged by the discoveries of radiant heat and electromagnetism. But with difficulties in the theory of heat and new fashions in science, the imponderable fluids evaporated. A new standard model was drawn up, based on the unification of light with electromagnetism, heat with kinetic energy, and magnetism with vortical motion, which strove to manage with one sort of material substrate, or ether, subject to the laws of mechanics. In the most austere of these GUTs, the "vortex atom," developed especially by William Thomson (Lord Kelvin), James Clerk Maxwell, and Joseph John Thomson, all physical phenomena were to be referred to motions of a single, perfect, incompressible space-filling medium.

The program of mechanical reduction, the standard model of the late nineteenth century, collapsed under experimental discoveries and difficulties in the theories of radiant heat and electrodynamics. The discovery of the electron and subsequent speculation about atomic structure suggested that matter might be built from three ingredients: in today's language, a negative lepton (electron), a positive baryon (proton), and, after the Compton effect, a neutral photon. But the study of the nucleus and cosmic rays between the world wars, and the building of ever more powerful accelerators after World War II, revealed many more "particles" than three. The gigantic instrumental and theoretical effort to classify and comprehend this cornucopia resulted in the standard model of the 1980s.

Like the decuplet of five pairs of twin brothers who ruled Atlantis, the standard model with its three pairs of leptons, eight gluons, and so on, will slip into the sea. Its place may be taken by uncountable numbers of unimaginably small, wriggling, vibrating bits, as in string theory, the latest candidate for the Theory of Everything.

J. L. Heilbron

STEREOCHEMISTRY. Although the founder of the atomic theory, John Dalton, speculated about the three-dimensional arrangements of atoms within molecules, chemists customarily specified formulas without any indication of the structure of molecules, much less the arrangements of their atoms in space, until the 1850s.

Jean-Baptiste Biot noted in 1811 that quartz crystals were "optically active;" when he directed polarized light through them, the plane of polarization rotated. This asymmetrical effect on light suggested that the atoms of the crystals might be arrayed asymmetrically. Further studies revealed that certain organic materials were also optically active, even in solution. Since a dissolved substance cannot have a crystal array of any sort, the asymmetry in these instances had to inhere in each molecule.

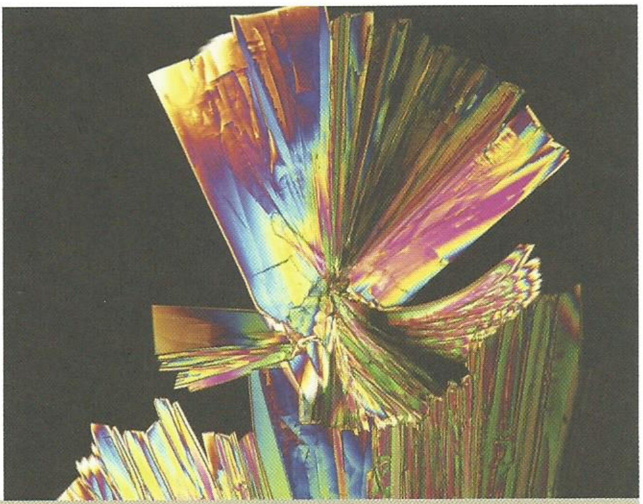
In his first important scientific investigation (1848), Louis Pasteur studied the crystal structures of the salts of the optically active tartaric acid and of an isomeric substance, the optically inactive "racemic" acid. He discovered that a certain racemate salt consisted of intermixed crystals, all of which appeared to be identical. More careful examination, however, revealed minute differences of form, from which Pasteur could distinguish mirror-image pairs of crystals, half right-handed and half left-handed. Separating them painstakingly by hand, Pasteur showed that the two mirror-image crystals rotated polarized light in equal but opposite directions. It was then clear that the natural racemate was optically inactive only because the two kinds of crystals were normally present in equal numbers, canceling out each other's activities. The artificially separated right-handed racemate was identical in optical activity to the naturally active tartrate.

Pasteur's research gave impetus to the chemical study of the three-dimensional structure of molecules (later called "stereochemistry"), but real progress came only after the formulation of the theory of chemical structure (1858), when chemists first began to have confidence in their ability to discern molecular architecture. The chief architect, August Kekulé, regarded designing molecules in three dimensions as still too difficult, hence premature. Kekulé proposed that every carbon atom could form bonds to precisely four other atoms—that it was tetravalent. In this way carbon atoms could link up together to form chains, the backbones of organic molecules.

A Dutch student of Kekulé's, Jacobus Henricus van't Hoff, provided the first substantial development of stereochemistry in 1874. (Entirely independently, a Frenchman, Joseph Le Bel, published a substantially similar exposition just two months later. Curiously, the two men had studied together with the noted Parisian chemist Adolphe Wurtz earlier that year, but apparently owed nothing to one another.) Van't Hoff taught that the four bonds of the carbon atom should be positioned as far apart from each other as possible, or (equivalently) that they be symmetrically situated in space. Uniform distribution of four bonds coming from a central point in two dimensions would place them at right angles, but in three dimensions they would have to be arranged tetrahedrally, with angles of about 109 degrees between adjacent bonds.

Van't Hoff demonstrated the empirical power of this purely theoretical idea by referring to the numbers of isomers known for various formulas. If carbon compounds were flat, there would have to be many more isomers than chemists had found to date. If carbon bonds formed symmetrically in three dimensions, on the other hand, the predicted isomer numbers matched those known. A crucial case emerged whenever the four groups attached to a given carbon atom were all different. Van't Hoff showed that in the tetrahedral bonding situation, exactly two different

John Ellis (b. 1946), a British theoretical physicist, helped to unify string theory and the standard model, and coined the phrase, "Theory of Everything," on which he appears to be working here.



Polarized-light micrograph of crystals of tartaric acid, one of a pair of compounds that gave rise to the concept of molecular isomerism

arrangements of the four groups in the form of nonsuperimposable mirror images would be possible. One of these molecules would be right-handed, the other left-handed. An organic molecule with such asymmetry should normally exhibit optical activity.

And so it was, at least to a first approximation. The accepted formula of Pasteur's tartaric acid showed the presence of two asymmetric carbons. The two possible mirror-image formulas centered on one of these atoms suggested the existence of a right- and left-handed version of the acid. Such "optical" isomers became known as "enantiomers," and any equal mixture of two enantiomers became known in the general case as a "racemic mixture." After a decade of hesitation, most chemists accepted the van't Hoff-Le Bel theory, and began to pursue the new field of stereochemistry with enthusiasm.

The earliest supporter of van't Hoff had been the Leipzig chemist Johannes Wislicenus. In 1887, Wislicenus published a pathbreaking study of what he called "geometric" isomerism, a kind of stereoisomerism not related to optical activity. In Heidelberg, Victor Meyer (who coined the term "stereochemistry") demonstrated the chemical effect of large space-filling groups on organic molecules; he called this phenomenon "steric hindrance." In Zurich, Arthur Hantzsch and Alfred Werner investigated the stereochemistry of organic compounds containing nitrogen, and Werner later applied stereochemical precepts to the chemistry of inorganic coordination compounds. Emil Fischer in Berlin used stereochemistry to interpret his fundamental research on carbohydrates.

These examples only highlight the vigorous activity in the new field toward the end of the century. In the next generations, many new ideas and research programs appeared alongside established ones. From early important work by Adolf von Baeyer on the stereochemical analysis of cyclic organic compounds came a substantial research program on "conformational analysis." Other chemists showed that Meyer's phenomenon of steric hindrance gave rise not just to stereoisomers, but in certain circumstances to optical activity. The problems of determining not just the relative, but the absolute configurations of atoms have been solved. The stereochemistry of ever more complex natural products was slowly unraveled. Today, chemists talk about the orientation of invisibly small atoms in space as comfortably as they talk about directions on a street map.

A. J. Rocke

STRATIGRAPHY AND GEOCHRONOLOGY. The principles of stratigraphy—the study of the earth's strata or layers of sedimentary rock—and of geochronology—the naming and describing, though not necessarily dating, of the periods of earth history—were established rapidly between 1810 and 1840. For the next century, stratigraphers filled

Looking southwest from Bright Angel Point at Grand Canyon National Park.

in the details of the stratigraphic column with ever-greater precision. Much of this research could be put to good use by the mining industry, and from the 1920s and 1930s by the petroleum industry.

Although stratigraphy flowered in the first half of the nineteenth century, it had its roots in the seventeenth century. The Danish Cartesian Niels Stensen (or Steno), in his *Produmus to a Dissertation on Solids Naturally Contained within Solids* (1669), considered bodies that made up the earth, particularly fossils, crystals, and strata. In any sequence of undisturbed strata, he concluded, the oldest strata would be on the bottom and the youngest on the top. This was an early version of the first of the three major principles of stratigraphy—the principle of superposition.

The second principle—that rock types or lithology usually occur in a predictable sequence—followed from the work of eighteenth-century mineralogists in the German states, Italy, France, the British Isles, and Russia. Independently of one another, they became convinced that the strata of the earth occurred in the same order everywhere. On the small scale, they knew that in an individual mining area, for example, they would find the same rocks in the same sequence in adjoining shafts. On a grander scale, they believed that around the globe, the rocks could be sorted into three main groups that appeared to represent a time sequence: the primary rocks, hard and often crystalline; the secondary rocks, softer, layered, and often fossiliferous; and the tertiary rocks, the topmost and softest rocks. Unfortunately, the principle of superposition failed when strata had been disturbed subsequent to deposition, and the principle of lithological regularity broke down when rocks of the same lithology occurred more than once in the sequence.

By the second decade of the nineteenth century, the third principle of stratigraphy—that fossils can be used to identify and correlate strata—had been established. For the next century and a half, paleontology was to be chiefly a tool for stratigraphy. Armed with these three principles, geologists between 1820 and 1840 established and named the greater part of the stratigraphic column, an accomplishment that has held up in outline to the present day. In practice, it involved one controversy after another about particular puzzles in the sequence. The British played a large part, perhaps because the strata of England are relatively straightforward.

In 1815, a mineral surveyor, William Smith, had published a map of the strata of England that although not fully correct, made a good start. Charles Lyell gave names to the epochs of the Tertiary—Pleistocene, Pliocene, Miocene, and Eocene—and distinguished them by their proportion of still extant fossils. Adam Sedgwick renamed the older part of the Secondary formations, the Paleozoic. With Roderick Murchison, he introduced the names Cambrian, Silurian, and Devonian. The Carboniferous and the renaming of the upper part of the older Secondary Mesozoic were English suggestions. The renaming gave birth to Permian (another Murchison coinage), Triassic (a German suggestion), Jurassic (largely French), and Cretaceous (Belgian). The establishment of geochronology was a magnificent achievement. Museum panoramas and book illustrations showing the development of life forms still encapsulate what the general public understands by geology.

More important within professional geology were stratigraphic maps, topographic maps colored to show the strata that outcrop at the surface of the earth. Geological mapping developed with great speed between the 1780s and the 1830s when most of the techniques employed until World War II were at hand. As cartography progressed and accurate topographic base maps that showed change of elevation by contours became more widely available, the task of making geological maps became easier. Stratigraphers used maps both as a record of their fieldwork and as a way to extract new information. Using them in conjunction with the stratigraphic column—a theoretical reconstruction of the strata arranged according to age—and the section—the vertical arrangement of strata along some line or traverse across the surface of the map—they could construct a mental picture of the three-dimensional structure of the strata and thus predict what would be found beneath any spot on the earth's surface.

Until the 1950s, most geological education gave priority to teaching students to construct and interpret maps, and professional stratigraphers were largely occupied with mapping the earth's surface. During the nineteenth century, they extended their mapping beyond northwestern Europe. They resolved problems about the Cambrian-Silurian boundary by introducing the Ordovician Period. American stratigraphers found that the Carboniferous did not work well for their territory, and replaced it with Mississippian and Pennsylvanian. The Canadians began trying to make sense of the afossiliferous pre-Cambrian rocks that made up much of their country.

Stratigraphers saw themselves as men who traveled widely, scaling mountains and descending mines, hammer, notebook, and map in hand, returning to their bases with packages of fossils and rocks to add to growing collections. Some were independently wealthy, but most found employment in universities and national geological surveys. In 1878, at the first International Geological Congress in Paris, they began the huge task of codifying stratigraphic nomenclature, a task that still continues.

Stratigraphers puzzled about how to reconcile the distinct breaks in the fossil record with the gradual changes predicted by evolutionary theory, writing at length about how elevation and erosion had destroyed part of the record. They worried that fossils might indicate changes in the environment of deposition rather than in the time of deposition. Walking through a gorge with sloping strata might be a walk through time or it might be a walk through space, from the deep ocean to a continental shelf to a brackish delta. With the growth of the petroleum industry, further subdividing the stratigraphic sequence became a necessity. New tools were developed, such as well logs and microscopical examination of microfossils, particularly foraminifera.

By World War II, the intellectual excitement in stratigraphy had evaporated. It revived after the war when stratigraphy was subsumed under the earth sciences, with their host of new concepts and sophisticated instruments.

Rachel Laudan

SUPERNOVA. Supernovae have been observed on several occasions, recently and spectacularly in 1885, when Ernst Hartwig saw a new star brighten the Andromeda galaxy by 25 percent. Six months later this supernova was ten thousand times fainter.

In 1911, the American astronomer Edward Charles Pickering differentiated between low-energy novae, often seen in the Milky Way galaxy, and novae seen in distant nebulae like Andromeda. By 1919, Knut Lundmark had realized that low-energy novae occurred commonly, whereas the brighter novae, up to tens of thousands times more luminous, occurred rarely. The 1920s saw two theories of these

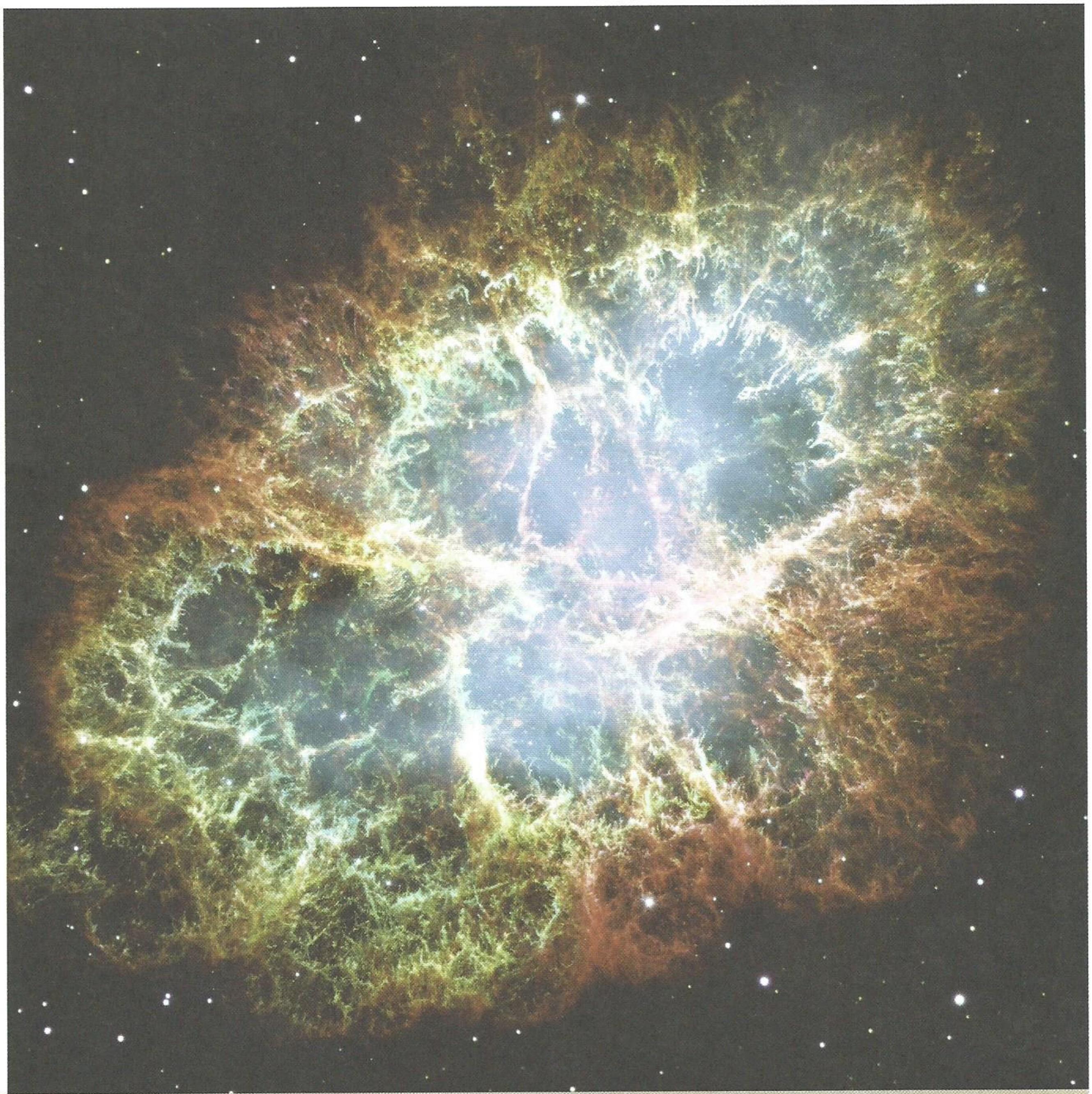


Image of the Crab nebula (M1), a remanent of the supernova seen on earth in 1054 A.D. The picture comes from data collected by the Hubble Telescope.

brighter novae (named "supernovae" by Fritz Zwicky and Walter Baade in 1934), one relying on runaway instabilities in stellar interiors, the other (by Alexander William Bickerton) suggesting that collisions had occurred between stars.

Zwicky started the first supernova detection patrol in 1933; J. J. Johnson joined him in 1936. Using the new 45-cm Palomar Schmidt Telescope they found twelve new supernovae in three years based on 1625 photographs of 175 extragalactic regions. The new 1.2-m Palomar Schmidt came into use after 1958, and by 1977 the supernova tally had reached 450.

In 1981, Gustav Tammann estimated that around three supernovae occurred every century in the Milky Way galaxy. Most go undetected due to obscuring interstellar material. During the last millennium local supernovae were detected only in 1006, 1054, 1572, 1604, and 1667.

The Taurus supernova of 1054 was extensively recorded in the East, being visible in daylight and reaching -5 in the magnitude scale. (The magnitude scale is a logarithmic scale of stellar brightness in which the brightest naked eye star is of magnitude 1, the faintest of magnitude 6. Hence, a negative magnitude denotes a body that is brighter than the brightest naked-eye star.) John Bevis discovered the expanding cloud of material that resulted in 1731. In 1758, Charles Messier labeled the cloud Ml, the first entry in his catalogue of nebulae. By 1937, OH, O III, N II, and SII emission lines (spectral lines emitted by excited atoms as they decay) had been found in the cloud. Owing to the large expansion velocity produced by the stellar explosion, the emission lines were particularly broad. After 1948, astronomers found several supernova radio sources.

In 1934, two years after the discovery of the neutron, Baade and Zwicky suggested that supernovae arose when giant stars became neutron stars. Their view became generally accepted after Jocelyn Bell Burnell discovered pulsars in 1967. The Crab Nebula pulsar came to light in 1969.

Over 120 supernova remnants have been discovered in the Milky Way. One type, exemplified by Cassiopeia A and the Veil nebula in Cygnus, has a ring-like structure. Others are irregular with a central brightening, like the Crab.

In the mid-1950s, astronomers recognized two supernova varieties. Type I are binary white dwarfs. Mass accretion, pushing the star beyond the Chandrasekhar limit, triggers a wave of nuclear reactions and a flood of neutrinos, either destroying the star completely or leaving behind a neutron star. Type II results from the explosion of a young, massive giant star that has exhausted its nuclear fuel. In February 1987 a Type II supernova exploded nearby, in the Large Magellanic Cloud. The pre-nova star was a supergiant. In exploding, its brightness increased by 10^8 in a few hours. The visible energy release of 10^{44} joules was dwarfed by the 10^{46} joules of high-energy neutrinos, many of which were captured by atomic nuclei thus manufacturing elements heavier than iron. The explosion scattered these elements far and wide throughout the galaxy.

David W. Hughes

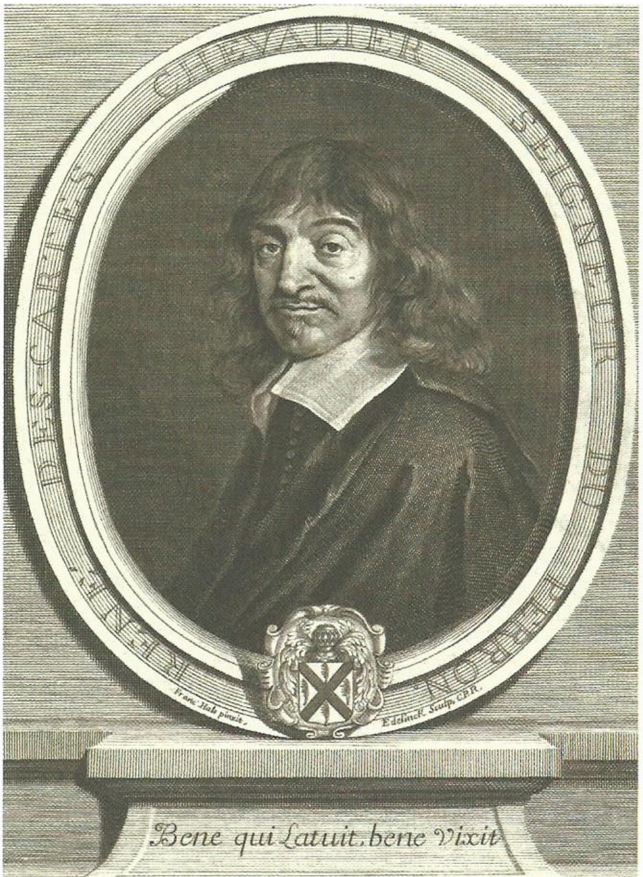
SYMPATHY AND OCCULT QUALITY. Aristotelian physics was strong on classification (four elements, four causes, types of motion, categories of being) but weak on dynamics (generation, corruption, physical interaction). Bodies acted on one another primarily through the "manifest active qualities" of the elements predominating in their constitutions: hotness, coldness, dryness, and moistness. Thus, to take a complicated example used by Aristotle, the sun melts wax and dries mud, the different consequences of the same manifest quality (hotness) depending on the elementary makeup of the recipient body. Two other widespread attributes of matter, gravity and levity, were often treated as if they were manifest qualities, since they characterized the four elements even though they could not be reduced to the tangible qualities hotness, coldness, and so forth, to which Aristotle gave priority.

The world has many physical properties less widely encountered than gravity and levity but, like them, not easily or obviously explainable in terms of the action of manifest qualities. Later Peripatetic philosophy designated these properties "occult," because, although evident in their consequences, their causes were hidden. The exemplar of an occult quality was magnetism. The ancients knew it as the ability of a peculiar rock to draw bits of iron to it—but why only iron? The answer lay, according to the natural philosophy taught when Galileo was in school, in an innate sympathy or harmony between lodestones and iron. This example indicates the level of explanation that, in the seventeenth century, made "occult" a byword for nonsense. Originally an expression that aided the classification of properties whose causes were provisionally unknown, the occult became a trash heap of innate and irreducible qualities. A purge or poison, the deadly glance of the basilisk, astrological influences, the powers of talismans, and the force by which that small pesky fish, the remora, stops big ships—all operated by occult sympathies and antipathies between agent and recipient. Molière neatly satirized the level of explanation afforded by the occult in his *Malade imaginaire* (1673), in which he praises a doctor for ascribing the soporific quality of opium to an occult "dormative virtue."

The mechanical philosophy, especially in its radical form of René Descartes's limitation of the affections of matter to extension, shape, and motion, appealed to the scientific revolutionaries of the seventeenth century because it annihilated the complex of qualities taught by the traditional philosophy they opposed. Even manifest qualities had to go; the hot, cold, moist, and dry became secondary effects arising from the interaction of the few primary qualities of extended, moving, material bits with the human sensory apparatus. Explanations in mechanical terms, like Descartes's referral of thunder and lightning, and rains of blood, to the precipitous fall of one cloud on another, might appear no more persuasive than magnetic sympathies; nonetheless, the corpuscular philosophy, by seeking a mechanical account of properties held by its opponents to be innate and irreducible, opened the possibility of further analysis. Robert Boyle's concept of the "spring of the air," for which he offered several mechanical analogies, and Descartes's representation of magnetism by a vortex of specially shaped particles, suggest the range and limitations of seventeenth-century mechanical models.

Against the rhetorical and explanatory advantages of the corpuscular philosophy, Isaac Newton's apparent invocation of an occult sympathy—the "universal attraction" of the *Principia* (1687)—seemed retrograde to many natural philosophers enlightened by Descartes. They were both right and wrong. Newton did return to an occult quality, but in its most useful and responsible form: a widespread property of matter, exactly described, whose cause had not yet been found. Newton's famous phrase "hypotheses non fingo" ("I feign no hypotheses") meant that, as far as he was concerned, gravity would remain occult. Until we have a Theory of Everything, and perhaps even then, scientists necessarily will continue to invoke occult qualities.

J. L. Heilbron


RENÉ DES CARTES CHEVALIER SEIGNEUR DU PERRON
Franc. Hals pinxit
Edelinck Sculp. CPR
Bene qui Latuit, bene Vixit

René Descartes (1596–1650), French mathematician and philosopher, whose mechanical world picture had no place for occult qualities

T

TELESCOPE. Lenses for reading were available in Italy in the thirteenth century, but not until the seventeenth century did spectacle makers in the Netherlands put together a device "by means of which all things at a very great distance can be seen as if they were nearby." In 1609, Galileo Galilei heard rumors of spyglasses, made more powerful ones, and pointed them at the heavens. In 1611, Johannes Kepler explained the path of light rays through lenses and the formation of images. The improved Kepler telescope formed images in its focal plane, where they were viewed by a magnifying lens.

Anything placed in the focal plane of a telescope appears sharply alongside the celestial object, as the Englishman William Gascoigne noticed in about 1640 when a spider spun its web inside his instrument. Astronomers inserted cross hairs, facilitating precise alignment of telescopes on objects, and micrometers, to measure small angular distances and diameters. They also developed, though more slowly, stable, precise mountings and large arcs with precisely divided and marked scales against which the telescope's alignment could be noted when pointed at a celestial object. Still their instruments suffered from chromatic and spherical "aberrations"—fuzziness of the image—arising from the fact that different wavelengths or colors of light are refracted by different amounts, and light incident on the periphery of the lens focuses closer to the lens than does light striking near the center. To reduce the aberrations, astronomers ground lenses with very long focal lengths, which led to long and unwieldy instruments. In 1757, the Englishman John Dollond perfected the achromat, a combination of glass lenses that brought rays of different colors to the same focus, enabling more precise measurements of positions of faint stars by means of shorter instruments easier to use. Inability to make large pieces of optical-quality glass, however, limited the size of refracting telescopes, in which light passes through transparent lenses.

The one-arm Estonian-German optical engineer Bernhard Voldemar Schmidt (1879–1935), known for the design of the Schmidt telescope, in which a glass corrector plate of complicated figure placed in front of the primary mirror creates an instrument almost free from optical aberrations. Usually used as a camera, the Schmidt telescope revolutionized optical astronomy.

In 1668, Isaac Newton, having decided that chromatic aberration in lenses could not be defeated, built the first successful reflecting telescope. It employed a concave mirror to collect light and form the image. William Herschel in England built telescopes with large reflecting metal mirrors in the 1780s and William Parsons in Ireland built the 6-foot "Leviathan of Parsonstown" in 1845. Giant reflectors, though producing spectacular observations, ultimately were disappointing: the mirrors flexed under their immense weights and tarnished quickly.

The second half of the nineteenth century saw advances in refracting telescopes, especially by the Boston firm of Alvan Clark and Sons. Their metal tubes were stiffer yet lighter than wooden telescopes. Larger pieces of optical glass were now available, from France and England, and five times the Clarks figured the lens for the world's largest refracting telescope, culminating in a 40-inch lens in 1897. It is yet to be surpassed in size. Larger pieces of optical glass are difficult to cast; heavier lenses flex more; and thicker lenses absorb more light.

Lenses also absorb strongly in the blue region of the spectrum, where photography is most effective. A new interest in astrophysics and distant stars required a new technology. George Willis Ritchey made the photographic reflecting telescope the basic instrument of astronomical research, constructing at the Mount Wilson Observatory a 60-inch telescope in 1908 and a 100-inch in 1918. Later the Rockefeller Foundation paid for a 200-inch reflecting telescope at nearby Mount Palomar. Corning Glass Works cast the mirror in 1934 as a thin piece of Pyrex glass with a system of ribbing in the back. Grinding the lens removed five tons of material, leaving sixteen tons of curved mirror, which received its reflective coating of aluminum in 1949.

To circumvent the problems of casting and supporting large mirrors, many small mirrors can be assembled into a close array. The Keck Telescope, erected in Hawaii in 1993, has thirty-six 1-meter mirrors mounted together on a tracking structure, and the European Southern Observatory in Chile links four 8-meter and three 1.8-meter mirrors into one very large telescope. Its huge cost is shared among nine countries.

Reflecting telescopes bring only rays from stars in the center of the viewing field to a sharp focus. Given a usable field of view of 15 seconds of arc, approximately a million photographic plates would be required to cover the entire sky. In 1930, Bernhard Schmidt, an Estonian-born optician at the Hamburg Observatory, designed a reflecting telescope with a usable field of view of 15 degrees. The Schmidt telescope has a simple spherical mirror plus a thin correction plate for spherical aberration. Palomar completed a 1.2-meter Schmidt telescope in 1948.

Non-optical telescopes can detect radio and gravitational waves unblocked by the earth's atmosphere. Other non-optical telescopes rise above the earth's atmosphere. There X rays incident on mirrors at small "grazing angles" are reflected into a detector, where their interaction with an inert gas generates countable electrons. The telescope, with several mirror surfaces nested concentrically within it, looks like a funnel. Telescopes in space also detect infrared emissions and gamma rays.

The Hubble Space Telescope enables traditional, optical astronomers to escape our atmosphere. The telescope's primary mirror is eight feet in diameter. Including recording instruments and guidance system, the telescope weighs twelve tons. It has been called the eighth wonder of the world; critics say it should be, given its cost of two billion dollars. It was as much a political and managerial achievement as a technological one; approval for it came only after a political struggle lasting from 1974 to 1977. In 1990, after overcoming a host of problems, its designers launched it into space, only to discover that an error had occurred in the shaping of the primary mirror. One newspaper reported "Pix Nixed as Hubble Sees Double." Addition of a corrective mirror solved the problem.

Over four centuries the telescope has evolved from two small glass lenses affordable and operable by an untrained individual of no great wealth into an immense political, managerial, and technological undertaking beyond the reach of all but the wealthiest countries. Our understanding of the universe has expanded apace, as ever larger, more expensive, and technologically sophisticated telescopes range over ever more of the electromagnetic spectrum to detect ever more distant objects.

NORRISS S. HETHERINGTON

TERRESTRIAL MAGNETISM. Practical needs, particularly of navigators, have inspired interest in terrestrial magnetism since at least the fifteenth century. Equally important have been conceptual puzzles about how to reconcile terrestrial magnetism with basic physical theory and with theories based on laboratory studies of magnetism. Consequently interplay between field studies and experimental studies has been a regular feature of the history of geomagnetism. So has a tension between explaining the ultimate causes of geomagnetism, usually in terms of some kind of fluid movement in the interior of the earth, and surveying the spatial and temporal variations of geomagnetic declination, dip, and intensity.

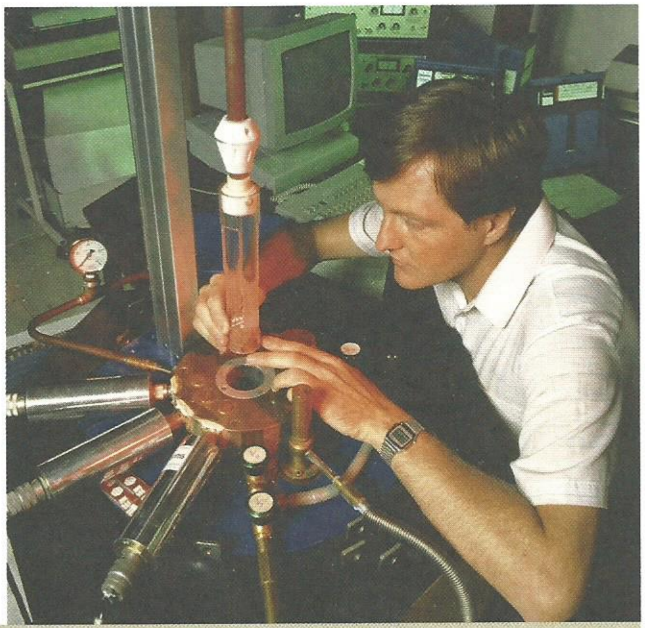
Serious work on geomagnetism began in 1600 with the publication of William Gilbert's *De magnete.* By that date, navigators knew that their needles sometimes pointed at an angle to true north (declination) and that sometimes they inclined from the horizontal (dip). Philosophers generally assumed that the earth's magnetism arose through the occult properties of the mineral magnetite or by some Neoplatonic correspondence between the polestar in the heavens and the magnetic north pole on Earth.

Making a magnet by hammering a hot iron rod aligned with the earth's magnetic field. William Gilbert, De magnete (1600), color added.

Gilbert, a member of the Royal College of Physicians in London, discussed the five motions associated with magnetism—attraction (he called it coition), orientation, declination, dip, and rotation—as a preliminary to presenting his theory of earth magnetism. Experiments with small magnetic needles on a small spherical lodestone (called a terella) showed that irregularities in the lode-stone changed the orientation of the needles. They also demonstrated that needles parallel to the surface of the sphere at the equator gradually dipped to a vertical as they moved to the position at the poles. The Earth, he concluded, was a giant lodestone with an immaterial rotating magnetic soul.

Because magnetism, including geomagnetism, seemed an exemplary occult force, mechanical philosophers had to find an alternative explanation in terms of matter in motion. In his *Principles of Philosophy* (1644), René Descartes traced the earth's magnetism to circulating streams of corkscrew-shaped particles. From this suggestion arose the tradition, predominant until the 1820s, of attributing the earth's magnetism to subtle active magnetic fluids. Edmond Halley in 1683 and again in 1692 proposed that the earth consisted of an inner sphere and outer shell. They rotated at different speeds and each had a north and south pole. The interactions between these four poles accounted for the variations in declination and dip. Between 1698 and 1700, Halley sailed the Atlantic, measured the variations in declination, and charted them on a pioneering map that appeared in different editions between 1701 and 1703.

Descartes's effluvial theory continued to be important until the early nineteenth century. The alternative, most fully articulated by Charles Augustin Coulomb and Simeon-Denis Poisson—whose theory presented to the Paris Academy in 1826 represented the culmination of the tradition—assumed distance forces resulting from fluids locked in magnetic substances. Other important figures in the debate were Gavin Knight; Leonhard Euler, who with others won the prize of 1746 offered on the subject by the Paris Académie des Sciences; Franz Aepinus; and Jean-Baptiste Biot. Many researchers attempted to deal with earth magnetism though the requisite mathematics was dauntingly complex. During the 1820s and 1830s, theories (like Poisson's) based on "austral" and "boral" fluids were losing



The investigator is placing a rock core sample in a cryogenic magnetometer to determine the strength and alignment of its magnetic field.

their luster. Christopher Hansteen revived Halley's two-axis-four-pole model in his *Investigations Concerning the Magnetism of the Earth* (1819). To look for poles, defined either as regions of maximum magnetic intensity or of vertical dip, Hansteen traveled to Siberia around 1830 and James Clark Ross went to Canada. Although the two-axis theory did not win acceptance, the reintroduction of poles as an object of investigation, the attempt to mathematize the theory, and the expeditions brought fresh ideas and evidence to geomagnetic studies. In the same decades, Hans Christian Ørsted's discovery in 1820 that electric currents produce magnetic effects, Thomas Seebeck's discovery of thermoelectricity in 1822, and Michael Faraday's discovery in 1831 that magnetism can produce electric currents gave rise to new questions and possibilities concerning earth magnetism. Alexander von Humboldt, who had been fascinated by the global variations of magnetism since the 1790s, speculated about the similarities between lines of equal magnetic intensity and isothermal lines and about interconnections between geological, meteorological, and magnetic phenomena. In 1805, he reported that magnetic intensity varied across the earth's surface. To plot these variations, Humboldt encouraged the establishment of a network of magnetic observatories. By 1834, the twenty-three European observatories had detected the phenomenon of magnetic storms. In the fifth volume of his *Cosmos* (1845), Humboldt summed up the state of knowledge of magnetic variation, distribution, and storms.

In the 1830s, Carl Friedrich Gauss and his younger collaborator Wilhelm Weber took over from Humboldt as leaders in geomagnetism, tackling problems from instrumentation to basic theory. Early in the decade Gauss designed the bifilar magnetometer, developed for the first time an absolute measure of magnetic intensity, and launched his own version of the Magnetische Verein (magnetic union) to establish a network of magnetic observatories worldwide. The results from these observatories came out in six volumes, *Resultate aus den Beobachtungen des magnetischen Vereins,* between 1836 and 1841. With new data about variations of magnetic intensity in hand, Gauss could publish his mathematical analysis of the vertical and horizontal components of earth magnetism in 1839. He analyzed the magnetic potential at any point on the earth's surface by an infinite series of spherical functions. Not dependent on a theory about the ultimate causes of geomagnetism, his method of analysis shaped theoretical work on geomagnetism for the rest of the century.

In Britain, a follower of Hansteen, Edward Sabine, fretted that Britain was letting slip the chance of contributing to the growing field of geomagnetism. In 1838, he enlisted the astronomer John Herschel to help him raise support for a British magnetic survey. The publication of James Clerk Maxwell's *Treatise on Electricity and Magnetism* in 1873 encouraged investigators to speak of the earth's magnetic field, not its magnetic forces, and gave them another set of mathematical tools.

Between 1890 and 1900, geomagnetism began to take on the trappings of a separate discipline. A new generation of mathematically trained physicists, notably Arthur Schuster, continued working on mathematical analyses of the earth's field although they did not propose new comprehensive theories. With the establishment of national surveys and observatories, the amount of data available multiplied. The beginning of submarine warfare accelerated military interest in geomagnetism. International organizations expanded; in 1896 the journal *Terrestrial Magnetism* was founded. Another period of rapid breakthroughs in geomagnetism occurred in the years following World War II. In 1947, following measurements of the magnetic fields of the sun and some stars, the English physicist Patrick Blackett suggested that magnetism (including the earth's magnetism) might be a property common to all rotating bodies. A decade earlier, Göttingen-trained physicist Walter Maurice Elsasser had published a series of papers suggesting that a self-excited magneto hydro dynamo in the earth's core created its field. For a few exciting years, scientists explored the consequences of the two theories in the hope of deciding between them. Then in 1952, after obtaining negative results from an experiment intended to detect the effects of rotation in the laboratory, Blackett himself rejected his own theory. Versions of Elsasser's theory held sway for the rest of the century.

Other major developments, interesting in their own right and for what they contributed to plate tectonics, occurred in paleomagnetism. Already in the nineteenth century, scientists had detected remanent or fossilized magnetism. They noticed that ferrous minerals in baked clays and cooled lava flows preserved the alignment of the earth's main field as it was when they had cooled. In the late 1950s, physicists in London, Newcastle, and the Australian National University who systematically surveyed remanent magnetism found that the magnetic north pole appeared to have wandered widely over the globe in the past. They proposed various hypotheses to explain this result: their instruments created the effect, the earth's field had not always been dipolar, the continents had moved relative to one another, or the earth's magnetic poles had wandered independently. By the end of the decade, a small but influential group of scientists, Keith Runcorn prominent among them, had convinced themselves that the continents had moved. This served to give the largely discredited theory of continental drift new life.

In the 1920s and 1930s, scientists had discovered another peculiarity about remanent magnetism. In some rocks the magnetism had a polarity opposite to that of the present geomagnetic field. In the 1940s, researchers in the Carnegie Institution of Washington developed a spinning magnetometer capable of detecting weak magnetic fields. From the 1950s through the 1960s, paleomagnetists at the United States Geological Survey and the Australian National University raced to reconstruct the history of these reversals, using radioactive dating to determine their sequence. By the mid-1960s, they had constructed a fairly complete scale. It proved to be a key piece of evidence for the theory of sea floor spreading.

RACHEL LAUDAN

THERMODYNAMICS AND STATISTICAL MECHANICS.

The development of the theory of heat in the first half of the nineteenth century, which eventually led to thermodynamics, was linked with the technology of steam engines. Their operation was originally analyzed in terms of the caloric theory, which represented heat as a conserved imponderable fluid. In 1824, the French military engineer Sadi Carnot employed the caloric theory in his analysis of an idealized heat-engine, which aimed at improving the efficiency of real engines. On the basis of an analogy with the production of work by the fall of water in a waterwheel, Carnot assumed that a heat-engine produced work by the "fall" of caloric from a higher to a lower temperature. The analogy suggested that the work produced was proportional to the amount of caloric and the temperature difference of the two bodies between which caloric flowed. Carnot proved that no other engine could surpass his reversible ideal engine in efficiency by showing that the existence of a more efficient engine would imply the possibility of perpetual motion. In 1834, a mining engineer, Benoit-Pierre-Émile Clapeyron, reformulated Carnot's analysis, using calculus and the indicator (pressure-volume) diagram. Carnot's theory was virtually ignored, however, until its discovery in the mid-1840s, via Clapeyron's paper, by William Thomson (Lord Kelvin), and Hermann von Helmholtz.

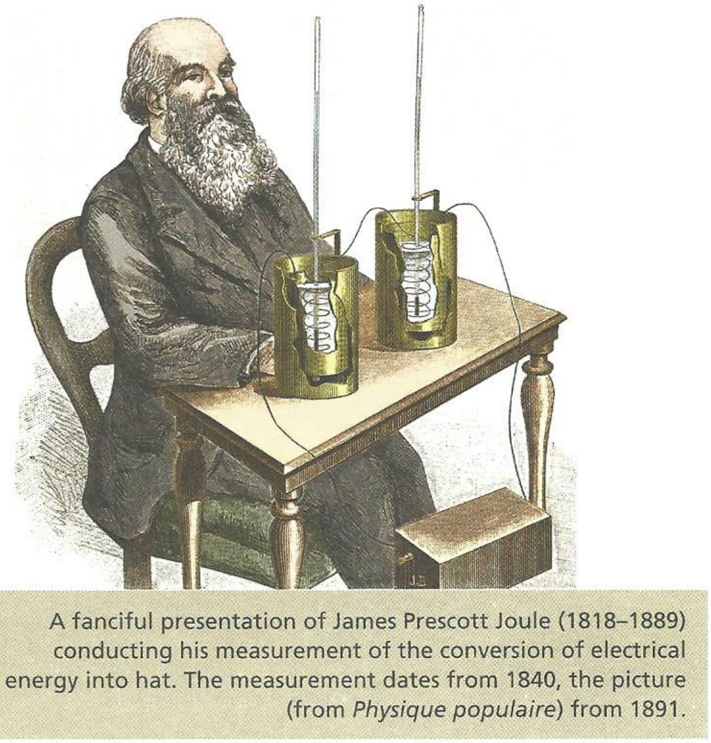
James Joule's experimental work of the 1840s, which indicated the interconversion of heat and work, undermined the caloric theory. His precise measurements supported the old idea that heat consists in the motion of the microscopic constituents of matter. The interconversion of heat and work, along with other developments spanning several fields (from theoretical mechanics to physiology), led to the formulation of the principle of energy conservation. In the early 1850s, all these parallel developments were seen, with the benefit of hindsight, as "simultaneous" discoveries of energy conservation, which became the first law of thermodynamics.

Joule's experiments, however, presented a problem for Carnot's analysis of a reversible heat-engine based on the assumption of conserved heat. In the early 1850s, Thomson and the German physicist Rudolf Clausius resolved the problem by introducing a second principle. Carnot's analysis could be retained, despite the rejection of the conservation of heat, because, in fact, it dealt with a quantity—the amount of heat divided by the temperature at which the heat is exchanged—that is conserved in reversible processes. During the operation of Carnot's engine, part of the heat dropped from a higher to a lower temperature and the rest became mechanical work.

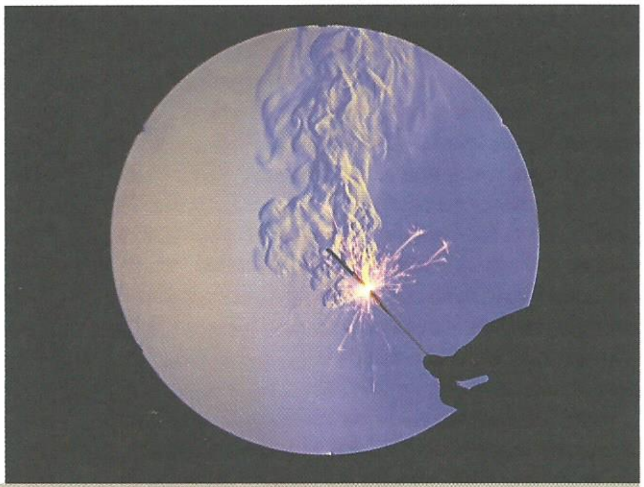
In 1847, Thomson diagnosed another problem, also implicit in Carnot's analysis. Carnot had portrayed heat transfer as the cause of the production of work. In processes like conduction, however, heat flows from a warmer to a colder body without doing any work. Since the heat does not spontaneously flow from cold to hot, conduction resulted in the loss of potential for doing work. Both Joule and Thomson agreed that energy cannot perish, or, rather, that only a divine creator could destroy or create it. Thomson resolved the difficulty in 1852 by observing that in processes like conduction, energy is not lost but "dissipated," and by raising the dissipation of energy to a law of nature. "Real"—that is, irreversible—processes continually degrade energy and, in a good long time, will cause the heat-death of the universe. The Scottish engineer William Rankine and Clausius proposed a new concept that represented the same tendency of energy toward dissipation. Initially called "thermodynamic function" (by Rankine) or "disgregation" (by Clausius), it later (in 1865) received the name "entropy" from Clausius, who grafted onto the Greek root for transformation. Every process (except ideal reversible ones) that takes place in an isolated system increases its entropy. This principle constituted the second fundamental law of thermodynamics, and its interpretation remained the subject of discussion for many years.

The dynamical conception of heat provided a link between mechanics and thermodynamics and led eventually to the introduction of statistical methods in the study of thermal phenomena. In 1857, Clausius correlated explicitly thermodynamic and mechanical concepts by identifying the quantity of heat contained in a gas with the kinetic energy (translational, rotational, and vibrational) of its molecules. He made the simplifying assumption that all the molecules of a gas had the same velocity and calculated its value, which turned out to be of the order of the speed of sound. Clausius's idealized model faced a difficulty, however, as pointed out by the Dutch meteorologist C. H. D. Buys Ballot. On the model, gases should diffuse much faster than actually observed. In 1858, in response to that difficulty, Clausius attributed the slow rate of diffusion to the molecules' collisions with each other and introduced the new concept of "mean free path," the average distance traveled by a molecule before it collides with another one.

In 1859, James Clerk Maxwell became aware of Clausius's kinetic interpretation of thermodynamics and, in the following years, developed it further by introducing probabilistic methods. In 1860, he developed a theory in which the velocities of the molecules in a gas at equilibrium distrib-



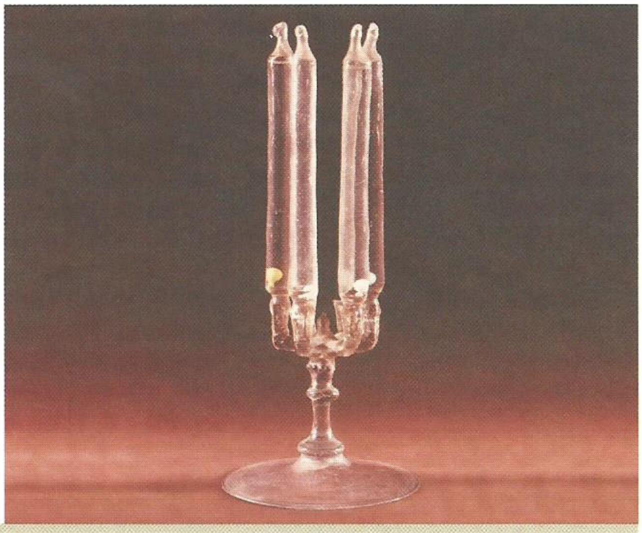
A fanciful presentation of James Prescott Joule (1818–1889) conducting his measurement of the conversion of electrical energy into hat. The measurement dates from 1840, the picture (from *Physique populaire*) from 1891.



Areas of different temperature on this sparkler are brought out by a technique that makes use of the dependence of the index of refraction of liquids on temperature.

ute according to the laws of probability. He inferred from "precarious" assumptions that the distribution followed a bell-shaped curve, the so-called normal distribution, which had been familiar from the theory of errors and the social sciences. Following up these ideas, he published in 1871 an ingenious thought experiment that he had invented four years earlier to suggest that heat need not always flow from a warmer to a colder body. In that case, the second law of thermodynamics could have only a statistical validity. A microscopic agent ("Maxwell's demon," as Thomson called it), controlling a diaphragm on a wall separating a hot and a cold gas, could let through either molecules of the cold gas faster than the average speed of the molecules of the hot gas, or molecules of the hot gas slower than the average speed of the molecules of the cold gas. Heat thus would flow from the cold to the hot gas. This thought experiment indicated that the "dissipation" of energy did not lie in nature but in human inability to control microscopic processes.

Ludwig Boltzmann carried further Maxwell's statistical probing of the foundations of thermodynamics. In 1868, he rederived, in a more general way, the distribution of molecular velocities, taking into account the forces exerted between molecules as well as the influence of external forces like gravity. In 1872, he extended the second law of thermodynamics to systems not in equilibrium by showing that there exists a mathematical function, the negative counterpart of entropy, that decreases as a system approaches thermal equilibrium. This behavior was subsequently called the "*H*-theorem."



Glass thermometers made for the Florentine Accademia del Cimento, which operated from 1657 to 1667

Furthermore, Boltzmann attempted to resolve a severe problem, pointed out by Thomson in 1874 and Joseph Loschmidt in 1876, which undermined the mechanical interpretation of the second law. The law defines a time asymmetry in natural processes: the passage of time results in an irreversible change, the increase of entropy. However, if the laws of mechanics govern the constituents of thermodynamic systems, their evolution should be reversible, since the laws of mechanics run with equal validity toward the past and the future. *Prima facie,* there seems to be no mechanical counterpart to the second law of thermodynamics.

Boltzmann eluded the difficulty in 1877 by construing the second law probabilistically. To each macroscopic state of a system correspond many microstates (particular distributions of energy among the constituents of the system), which Boltzmann ranked as equally probable. He defined the probability of each macroscopic state by the number of microstates corresponding to it and identified the entropy of a system with a simple logarithmic function of the probability of its macroscopic state. On that interpretation of entropy, the second law asserted that thermodynamic systems have a tendency to evolve toward more probable states. The interpretation came at the cost of demoting the law. A decrease of entropy was unlikely, but not impossible.

Maxwell's and Boltzmann's statistical approach to thermodynamics was developed further by J. Willard Gibbs, who avoided hypotheses concerning the molecular constitution of matter. He formulated statistical mechanics, which analyzed the statistical properties of an ensemble, a collection of mechanical systems. This more general treatment proved to be very useful for the investigation of systems other than those studied by the kinetic theory of gases, like electrons in metals or ions in solutions.

Theodore Arabatzis

THERMOMETER. The notion of a scale or degrees of heat and cold dates back at least to the second-century physician Galen, as does the idea of using a standard—such as a mixture of ice and boiling water—as a fixed point for the scale. Ancient philosophers' experiments, such as Hero of Alexandria's "fountain that drips in the sun," demonstrated the expansion of air with heat, and were known among natural philosophers of the sixteenth century. In the second decade of the seventeenth century, Galileo, Santorio Santorio, and others began to use long-necked glass flasks partially filled with air and inverted in water to measure temperature, applying them to medical and physical experiments and keeping meteorological records. The first sealed liquid-in-glass thermometers, filled with spirit of wine, were constructed for the Accademia del Cimento in Florence in 1654 by the artisan Mariani; though not calibrated from fixed points, his thermometers agreed very closely among themselves.

The succeeding century saw experimentation with thermometric liquids, among which spirit of wine was favored for its quick response and because no cold then known would freeze it. Several natural philosophers, including Robert Hooke, Christiaan Huygens, and Edme Mariotte, worked out methods for graduating their instruments from a single fixed point, typically the freezing or boiling point of water. Toward the end of the seventeenth century, Italian investigators began using two fixed points, as did the Dutch instrument maker Daniel Fahrenheit in the first few decades of the eighteenth century. Fahrenheit's excellent thermometers spread his method and his preference for mercury throughout England and the Low Countries, while the dominance of France and the fame of its Académie Royale des Sciences secured the position of academician René-Antoine Ferchault de Réaumur's thermometer on the rest of the Continent.

Réaumur and his contemporaries despaired of precision in their instruments. The inconstant composition of spirit of wine; air dissolved or trapped in the liquid, whether mercury or spirits; the lack of good glass—these and the lack of motivation to precision rendered the thermometer's readings at best qualitative indications of the temperature. After the Seven Years' War, the rational bureaucratic state and industrial manufacturers generated pressure for precise measurement for cartography and navigation, enclosures and canals, and the construction of steam engines and other machinery. In England, instrument making grew from a handicraft to an operation of industrial scale, exploiting advances in glassmaking and metallurgy and serving an international clientele. The thermometer played an auxiliary role in the precise measurements of the late Enlightenment, but from about 1760, the Genevan natural philosopher Jean-André Deluc developed methods for rigorously calibrating the instrument and for using it in exhaustive series of systematic measurements. In England, a committee of the Royal Society of London under the chairmanship of Henry Cavendish worked out methods in 1776 of setting the upper fixed point in a water bath, methods that remain in use today. Late-eighteenth-century thermometers achieved a precision of 1/10° F. The chief development of the nineteenth century was the discovery that the glass of new thermometers contracted in time so that their zero point fell; in the 1880s, glasses were developed that did not experience these effects.

Theodore S. Feldman

TRANSURANIC ELEMENTS. Glenn T. Seaborg popularized the term "transuranic elements" after the declassification of information on the elements with atomic numbers greater than uranium's.

The Rutherford-Bohr model of the atom, established between 1911 and 1922, explained for the first time why the lanthanides had similar properties—namely that they possessed identical outer electronic configurations and slightly different numbers of electrons in interior subshells. Both Johannes Rydberg in 1913 and Niels Bohr in 1921 speculated that a similar group of heavier elements might exist, and Vicktor Goldschmidt proposed that they should be named the neptunium group. Following the discovery of nuclear fission in 1939, Edwin M. McMillan and Philip H. Abelson, working at the University of California at Berkeley, showed that neutron bombardment of uranium produced a synthetic radioactive element. Because of its position in the periodic table following uranium (with its association with the planet Uranus), they followed Goldschmidt in naming it neptunium. At the same time, and using the Berkeley 150-cm (60-inch) cyclotron, Seaborg and his colleagues prepared plutonium (element 94) by the beta-decay of neptunium. McMillan and Seaborg received the Nobel Prize in chemistry in 1951 for this work. During the war, Seaborg found time to pursue further examples of synthetic transuranic elements. Americium and curium were identified between 1944 and 1945, and berkelium, californium, einsteinium, fermium, and mendelevium by 1953. Altogether Seaborg participated in the identification of nine of the fifteen actinides (as chemists called Goldschmidt's neptunides) between 1940 and 1970.

Although the chemistry of neptunium and plutonium proved analogous to uranium's, their successors did not. This anomaly forced a reexamination of their place in the periodic table. As early as 1944, Seaborg noted that elements 95 and 96 should have properties analogous to those of the lanthanides europium and gadolinium. He therefore suggested that elements 90–92 (thorium, protactinium, and uranium) should be moved from the seventh period of the periodic table to form a second rare earth (actinide) family of elements that extended from 89 (actinium) to 102 (nobelium), and subsequently to lawrencium, made in an accelerator in Berkeley in 1961 under the leadership of Seaborg's colleague Albert Ghiorso. This amendment to the periodic table proved the key to discovering the remaining elements. The preparation and confirmation of a few fleeting atoms of synthetic transactinides beyond lawrencium saw rival groups from the Soviet Union and Germany competing with the Americans. Settling the names of these synthetic elements, rutherfordium, dubnium, seaborgium, bohrium, and meitnerium, proved controversial and protracted. In the fifty years between 1940 and 1990, seventeen new elements were added to the periodic table beyond uranium.

Seaborg also speculated that beyond transuranic elements 113 and 164 there may be islands of stability containing super-heavy elements with long radioactive half-lives that would allow detailed comparisons with natural elements in their group positions within the periodic table. Besides forming an outstanding example of twentieth-century big science, the investigation of the transuranic elements has shown the continuing value and power of Dmitrii Mendeleev's periodic table.

William H. Brock

American nuclear chemist Glenn T. Seaborg (1912–1999), photographed in his laboratory at the University of California, Berkeley, in 1962

U

UNIVERSE, AGE AND SIZE OF THE. At the end of the seventeenth century, Isaac Newton's concept of an infinite universe created instantaneously by God rendered the question of the size of the universe moot and the question of its age a matter for historical rather than scientific determination. For more than two centuries after the publication of Newton's *Principia,* efforts to measure astronomical distances were confined to our solar system and a few nearby stars. Ever larger telescopes and the development of photography and spectroscopy greatly increased the variety and accuracy of the data available to astronomers, but at the end of the nineteenth century, the size of our own Milky Way galaxy was still unknown and, despite earlier speculations about the possibility of other systems, few, if any, astronomers believed that anything existed outside our own galaxy in the infinite void of the universe.

Between 1910 and 1930, new techniques for estimating interstellar distances finally enabled astronomers to determine the approximate size and shape of the Milky Way galaxy. During the same period, Vesto M. Slipher and Edwin Hubble measured the red shift in the spectra of a number of spiral nebula, and determined that almost all of them were moving away from the earth at high radial velocities. By 1929, Hubble had also calculated the distance to several nebula, and for the first time had provided convincing evidence that spiral nebula were clusters of stars (he did not identify them as galaxies) far beyond the borders of our own galaxy. Even more significantly, Hubble had found that the farther away the nebulae were, the greater their radial velocities away from the earth. Hubble's discoveries not only populated Newton's cosmic void with myriads of stars, they also suggested that the universe itself was expanding rather than static. The concept of an expanding universe had already been proposed theoretically by Willem de Sitter (in 1917), Alexander Freedman (1922), and Georges Lemaître (1927) as a way to resolve an anomaly in the solution to Einstein's theory of general relativity, but it was Hubble's work that caused astronomers to begin seriously to consider the idea of an expanding universe and the implication that it had a calculable age and size.

The key to calculating the age, and hence the size, of an expanding universe is the determination of the intergalactic velocity/distance ratio (which became known as the "Hubble Constant"). In the 1930s, Hubble's original value for the velocity/distance ratio produced an estimate of about 2×10^9 years for the age of the universe. This result briefly created the curious anomaly of a calculated value of the age of the universe that was smaller than radiometric measurements of the age of the earth. The work of Walter Baade in the 1940s and Allan Sandage in the 1950s resulted in substantial revisions in the accepted value of Hubble's Constant, and by the 1960s astronomers agreed that the universe was between 10 and 20×10^9 years old, with a corresponding size of the order of 10^{10} light-years. Also by the 1960s, the success of the "Big Bang" Hypothesis had provided astronomers with a causal physical model of an expanding universe with an instantaneous beginning and a finite age and size. Since the 1950s, the rapid proliferation of new techniques and technologies has enabled astronomers to probe ever closer toward the outer edge of the universe, and in the 1990s, a more precise rede-termination of the Hubble Constant was made a priority of the new Hubble Space Telescope. The results of the several independent efforts to recalculate the Hubble Constant were not consistent among themselves, however, and the late 1990s saw renewed controversy over the age and size of the universe. At the century's end, some astronomers believed that the universe's age had been determined to lie within the range of 12 to 15×10^9 years, while their more cautious colleagues remain unwilling to allow for a greater certainty than the earlier 10 to 20×10^9 years. The size of an expanding universe, of course, depends on its age, but recent cosmological theories, such as Alan Guth's inflationary model, suggest the possibility that our observable universe may be only a small part of a much larger structure.

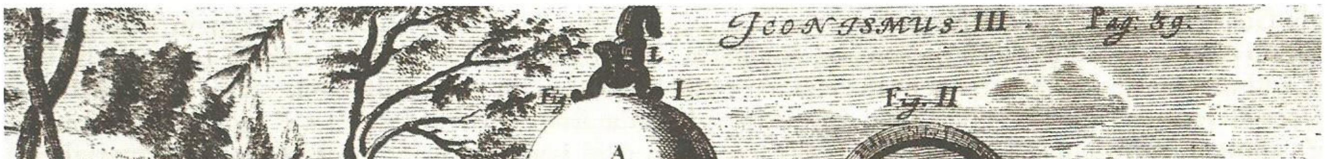
Joe D. Burchfield

V

VACUUM. Nature abhors a vacuum. So said medieval natural philosophers, following Aristotle. Against the ancient atomists, who held that material atoms move in an infinite void, Aristotle presented several arguments for the impossibility of a vacuum: the lack of resistance would produce infinite velocities; the homogeneity of the void precluded natural motion, which for Aristotle relied on a distinction between up and down; and the void likewise prevented violent motion, which needed an external medium for continued propulsion. The plenum persisted into the seventeenth century, notably in the system of René Descartes, who identified matter with space. But the possibility of the void received some discussion from medieval scholastics, who wondered in particular about the space beyond the stars, where God perhaps resided.

Experimental refutation of the *horror vacui* came in the seventeenth century. Mining pumps of the time operated according to the abhorrence of the vacuum, up to a point—thirty feet, in fact, above which they could not draw water. In 1644, an Italian mathematician, Evangelista Torricelli, explained the limitation by a mechanical equivalence between the weight of atmospheric air and the weight of the column of water, and demonstrated it using a glass tube, closed at one end, inverted in a basin of mercury. The mercury rose to a height one-fourteenth that to which water attained. Torricelli's new device—what we now call a barometer—figured in a famous experiment four years later by Blaise Pascal, who initially doubted Torricelli's explanation of the barometer and thought it showed only the limits to the force of a vacuum. Pascal pursued barometric experiments with a variety of liquids and glass tubes up to 14 m (46 ft) long, for the latter relying on the state-of-the-art products of the glass factory in his hometown of Rouen. In the decisive experiment, Pascal in 1648 sent his brother-in-law up a mountain in France with a barometer; the lower level of the mercury at the peak convinced Pascal and others that the weight of the atmosphere, not the vacuum inside the barometer, was forcing up the mercury in barometers and the water in mining pumps.

Otto von Guericke soon provided an equally famous demonstration using his new air pump, a piston-driven suction pump with valves that could suck the air out of sealed chambers and thus make a vacuum. In 1657, in Magdeburg, where he was the mayor, Guericke worked his air pump on



The experiment of the Magdeburg spheres (1654), named after the hometown of the inventor of the air pump, Otto von Guericke. A pair of hollow hemispheres easily separable under ordinary conditions could not be pulled apart by teams of horses when put together, sealed hermetically, and exhausted of air.

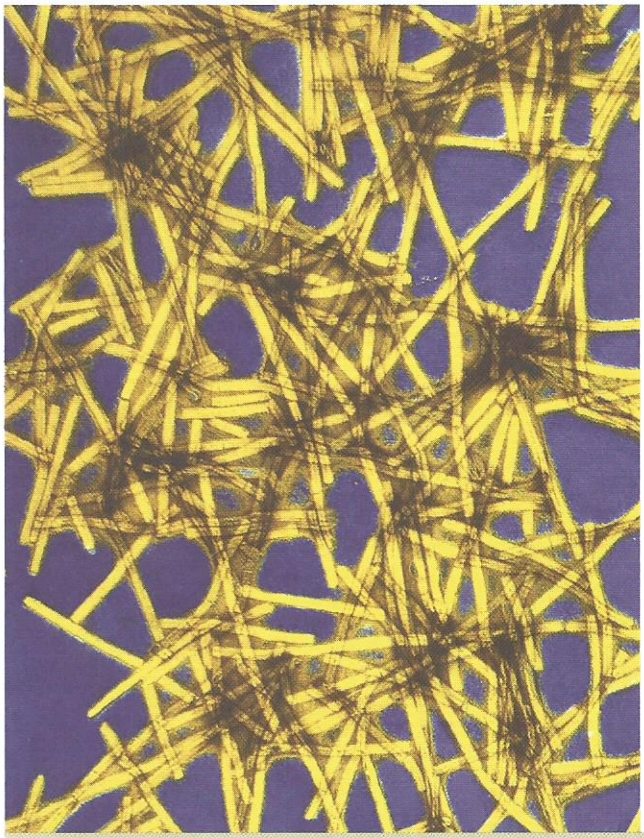
two copper hemispheres stuck together and showed that a team of horses could not pull them apart; the force of the vacuum—or, rather, of the air on the outside of the hemispheres—held them together. Robert Boyle developed the air pump into a means of easy production of a vacuum. When Boyle placed a barometer inside a glass globe, the level of mercury descended as the pump evacuated the enclosed space until the mercury no longer stood. Boyle's account of the results, *New Experiments Physico-Mechanicall Touching the Spring of the Air* (1660), showed along the way that cats and candles could not survive in a vacuum but that electric and magnetic effects could.

The technology of the vacuum would henceforth be crucial for modern science. The fruitful program of experiment with evacuated cathode ray tubes in the nineteenth century relied on a new generation of vacuum pumps, the first major advancements over von Guericke's original design; in particular, a pump made by German instrument-maker J. H. W. Geissler using a mercury column instead of pistons, which improved residual pressures from one inch to one millimeter of mercury. Rotary pumps made by Wolfgang Gaede in Germany in the early twentieth century proved crucial for the development of vacuum tube technology in the commercial electronics industry. High-energy particle accelerators later in the century required further advances in the production of large empty spaces.

The vacuum of physicists since the early modern period has not been empty. The imponderable fluids of electricity, light, and magnetism in Laplacian physics pervaded it, as did the ether and electromagnetic fields of Maxwellian electromagnetism. Even after Albert Einstein banished the ether, his postulated equivalence of energy and mass implied that matter could still intrude in empty space, and fields, electron holes, and ghost particles continue to clog up the vacuum of modern physics.

PETER J. WESTWICK

VIROLOGY. The term "virus" in its original Latin meaning (poison, morbid principle) was used up until the beginning of the twentieth century to indicate the causative agent in the transmission of a specific disease, as in the virus of cholera or the virus of rabies. In 1892, Dmitri Ivanovsky found that the virus of tobacco mosaic disease passed through a filter believed to trap all known bacteria. This observation gave rise to the concept of "filterable viruses." Martinus Willem Beijerinck conceived of this infectious agent as a "living contagious fluid" on the basis that only true fluids were filterable. Filtration made possible a new classification of infectious agents. Soon clinicians recognized that, in addition to tobacco mosaic virus (TMV), the agents of many well-known diseases such as rabies, hog cholera, influenza, poliomyelitis, herpes simplex, and vaccinia were filterable viruses. Thomas M. Rivers's influential textbook *Filterable Viruses* (1928) was the last major work to retain the term "filterable virus"; by the mid-1930s, "virus" alone would do. From 1900 to about 1930, some authors used the term "ultravirus" to emphasize the invisibility of these filterable agents to light microscopy, but this terminology was not widely adopted.



False-color transmission electron micrograph of the rod-shaped particles of tobacco mosaic virus

Although Beijerinck's concept of a contagious fluid would suggest a continuous, nonparticulate nature, except for bacteriophages (bacterial viruses), there seemed to be little challenge to the belief in the particulate nature of viruses. The bacteriological paradigm of tiny organisms seemed to dominate thinking about viruses, filterable and nonfilterable. The only controversy concerned the nature of bacteriophages. Their codiscoverer Félix d'Hérelle conceived of them as filterable viruses that infect bacteria. Scientists who believed in the simplicity of bacteria as a class of organisms fundamentally distinct from complex multicellular organisms resisted this concept. They also pointed to experimental results confounded by lysogenic behavior of some phage isolates. Lysogenic bacteria harbor the genetic material of a bacterial virus in a repressed state; under certain conditions, the virus can be induced to enter its regular growth cycle, which often kills the host cell. The analogy between the process of lysogenic virus induction to the then-recently discovered autocatalytic activation of proteases was advocated from 1920 to the mid-1940s by two Nobel Prize–winners, Jules Bordet and John H. Northrop. Their authority relegated the bacterial virus model for bacteriophage to a secondary status corrected only when electron microscopy made possible visualization of phages.

The microbial conception of viruses prompted attempts to study their metabolism and their growth in pure culture. It proved impossible to grow viruses in the absence of living host cells, and viruses were reconceptualized as obligate intracellular parasites. Viruses could be obtained only from infected plants, animals, or bacteria. Embryonated chicken eggs, and later animal cells in tissue cultures, became the standard laboratory media for growing animal viruses for diagnosis and study. Bacterial cultures, both in liquid media and on solid agar plates, provided the cells for growing. In a classic study of a virus disease, Edward Jenner confirmed common folk wisdom that prior sickness with a benign disease of cows, cowpox, protected humans from subsequent susceptibility to a lethal disease, smallpox. He exploited this finding to develop the procedure of vaccination. Louis Pasteur extended this procedure to several other diseases, both bacterial and viral. The use of attenuated or weakened strains of virus to induce mild or subclinical illness that confers immunity is the basis for vaccines developed against poliovirus through the work of John Franklin Enders and his colleagues Jonas Salk and Albert Sabin.

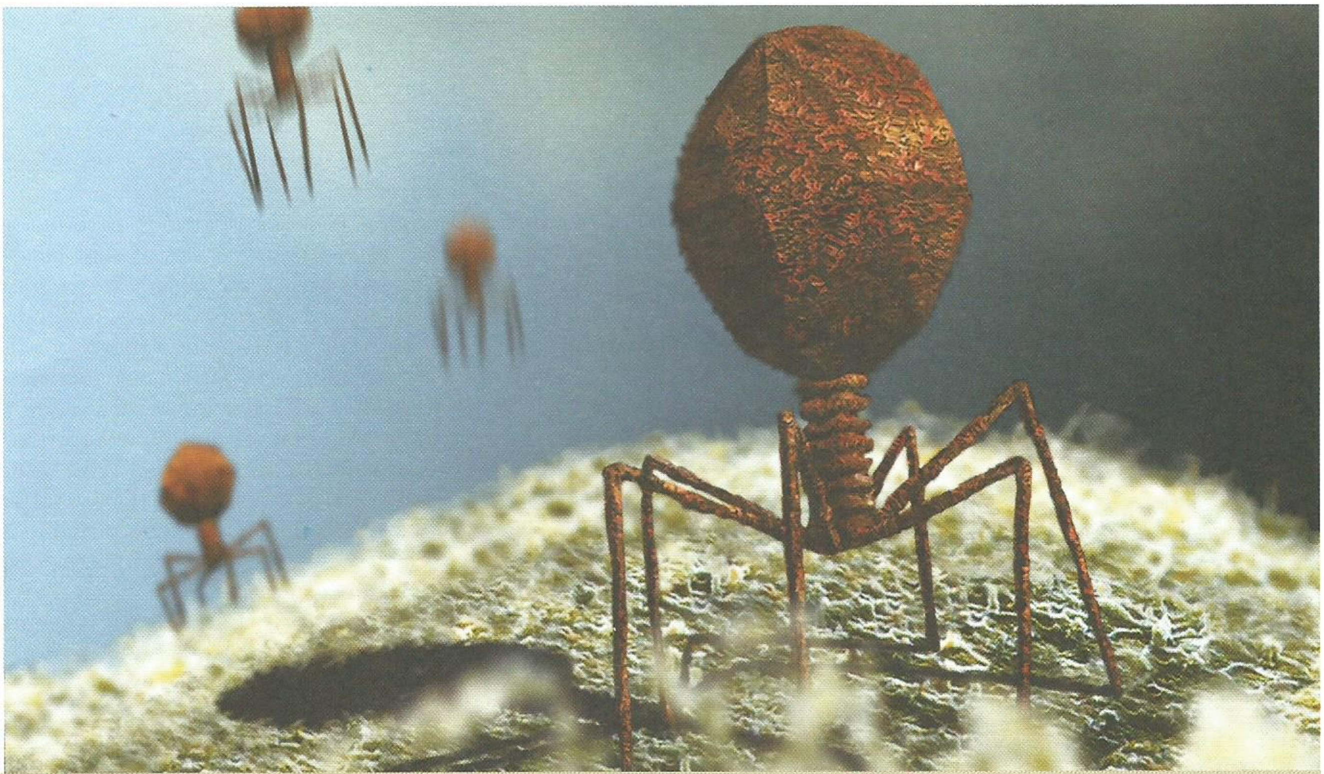
In the mid-1930s, Ernst Ruska and his colleagues turned the electron microscope they invented to the study of viruses. The higher resolution obtained with this instrument revealed the regular structures of virus particles, but also showed that viruses exist in many shapes, from simple rods such as TMV to elaborately tailed and "decorated" structures such as the T-even bacteriophages.

Chemical analysis of viruses became possible in the 1930s because of their purification by sedimentation in the ultracentrifuge. Initial analyses of some viruses such as TMV and poliovirus suggested that they were composed entirely of proteins, a finding that fit well with the notion that viruses resembled enzymes in both specificity and catalytic power. Soon, however, it was discovered that purified viruses always contained phosphate in the form of nucleic acids. The conception of viruses as simple nucleoprotein particles raised the conundrum of the living nature of such simple chemical entities. This paradox became especially acute when Wendell Stanley crystallized TMV and poliovirus in 1935, since crystallization was believed to be the ultimate criterion for chemical purity.

The chemical simplicity and rapidity of growth of viruses and the observation that they had heredity properties (such as the range of host species on which they grow) led investigators in the late 1930s to employ viruses to study the chemistry of the gene. Max Delbruck, Alfred D. Hershey, and Salvador Luria used bacteriophages as a model for gene replication and heredity transmission; their work helped to set the current directions of molecular biology. Alfred Geirer, Gerhard Schramm, and Heinz Fraenkel-Conrat used biochemical approaches to show that the genetic properties of TMV resided in the RNA component of the virus, not in the protein coat.

As more viruses were isolated from nature and studied, their diversity became apparent. One class, first represented by a virus that causes cancers in chickens (Rous sarcoma virus), was found to copy its RNA genome into DNA and integrate this DNA provirus into the host cell chromosome. This mechanism, first proposed by Howard Temin, seemed implausible because it required a reverse of the normal flow of genetic information. In 1970, both Temin and David Baltimore discovered the enzymatic mechanism for this process, demonstrating that it characterized a large class of RNA viruses, now known as retroviruses. When a mysterious immune deficiency disorder appeared in epidemiologically recognizable groups in 1982, virological studies soon identified the causative agent as a retrovirus, now called the human immunodeficiency virus (HIV).

William C. Summers



Computer artwork of T-bacteriophages (phages) attacking a bacterium, which will die after they have used its machinery to replicate themselves

W

WOMEN IN SCIENCE. Women have been and remain underrepresented in science. During the Scientific Revolution of the seventeenth century aristocratic women were active as both patrons and interlocutors of natural philosophers. For example, Queen Christina of Sweden patronized many natural philosophers, astrologers, and astronomers, including René Descartes and Gian Domenico Cassini; Princess Caroline of Wales coordinated Leibniz's activities in England, especially his debate with Isaac Newton via Samuel Clarke; and Queen Charlotte Sophia of England supported Jean André Deluc.

Some women gained access to the practice of science as wives or relatives of scientists who worked at a home base, whether an observatory or a museum—Caroline Lucretia Herschel, for example, who discovered eight comets, the sister of William Herschel and the aunt of John Herschel, England's leading astronomers for half a century. A few women attained positions of scientific leadership. The marquise du Chatelet, the friend of several eighteenth-century philosophers, notably Voltaire, made the first complete translation of Newton's *Principia* into French. Laura Bassi, professor of physics at the University of Bologna, was a protégée of the city's cultural aristocracy. Most women in science, however, were relegated to the supporting cast—collecting, illustrating, or entertaining.

In the nineteenth century, the professionalization of science and its increasing location in the laboratory moved science away from its domestic base. The transition further excluded women from science, because social pressure kept them tied to the home and child rearing. Nevertheless, some women made important contributions: Mary Somerville and Jane Haldimand Marcet in England through their informal textbooks and Maria Mitchell in the United States, who detected comets and taught science to many women at Vassar College. The rise of women's colleges in the last third of the century, as well as the willingness of some universities to allow foreign women to study or even graduate created the first generation of formally educated women scientists. For example, Sonya Kovalevsky, a Russian-born mathematician, obtained a Ph.D. in Germany in 1874, became a professor at Stockholm Holgsholz, a private school, and wrote books and plays advocating women's equality through education. In the twentieth century, the shortage of technical personnel during the two world wars temporarily opened further opportunities for women in science.

Women's place in science tended to vary significantly by discipline. They encountered substantial resistance in the laboratory sciences. They were more readily accepted in observational sciences such as botany and classical astronomy, where the need for large-scale collecting and observing encouraged the persistence of an amateur subculture for both men and women. Theoretical sciences—except for mathematics, in which there was an often explicit bias against women—also presented fewer barriers since the equipment and facilities required were minimal. Both observational and theoretical pursuits seemed tolerably compatible with women's primary familial responsibilities; observation additionally belonged to a socially acceptable tradition of amateur practice.

During the twentieth century, an increasing number of women, many of them aided by enlightened male mentors, excelled in the experimental as well as in the theoretical sciences. Among them were Marie Sklodowska Curie, a codiscoverer of radioactivity and radium, who worked in state-funded laboratories in Paris and won two Nobel Prizes; her elder daughter, Irène Joliot-Curie, who shared the 1935 Nobel Prize in chemistry with her husband Frédéric Joliot for discovering artificial radioactivity; Hertha Ayrton, who worked at the interface of physics and engineering with support from the feminist Langham Place Group and from her physicist husband William Ayrton, and who became the first woman nominated for fellowship in the Royal Society of London; Lise Meitner, a protégée of Max Planck, who headed the physics division at the Kaiser Wilhelm Institute for Physical Chemistry between the wars and figured in the

German chemist Ida Tacke Noddack (1896–1978) around 1930

French nuclear physicist and Nobel laureate Irène Joliot-Curie (1897–1956), at work in the Radium Institute in Paris in the 1930s

discovery of nuclear fission; and Rita Levi-Montalcini, who shared a Nobel Prize for her research in neurobiology.

British culture proved relatively conducive to the enrollment of women in science, to some extent because the British Empire provided scope for imagination, independence, and travel for women of the middle upper class. The biologist Dorothy M. Wrinch, born in the British colony in Argentina, distinguished herself in mathematics at Cambridge, became the first woman to receive a doctorate in science from Oxford (1929) and a pioneer of research in protein structure and molecular biology.

In Britain during the 1930s, socialist commitments helped others flourish within scientific partnerships such as those of Dorothy and Joseph Needham, Tony and Norman Pirie, and Kathleen Yardley Lonsdale and Thomas Lonsdale. Among the accomplished women scientists from this group was Dorothy Crowfoot Hodgkin, who won a Nobel Prize in chemistry (1964) for solving the structure of key biomedical compounds, most notably penicillin and vitamin B-12. Still others made their marks by venturing into offbeat areas of their disciplines, a career path exemplified by Barbara McClintock, who in 1983 received the Nobel Prize for her discovery of genomic transposition (jumping genes).

Still women continued to face discrimination in most fields of science, and many found it difficult to reconcile the demands of research with those of home and family. Some women scientists, believing that the demands of science could not be squared with the traditional role of women, remained single. Three-quarters of women scientists who did marry collaborated with their scientist husbands. But while a scientific marriage often facilitated acceptance into a broader scientific community, it often led colleagues to assume that the work of the wife was secondary to that of the husband.

Women scientists often had difficulty isolating the role of gender discrimination in their professional lives. For example, socialist women scientists who believed in the Marxist emphasis upon class as the dominant social relation long resisted the idea of struggling against gender bias because it would detract from the presumably more basic class struggle. Many other women scientists disliked claiming attention as women, as opposed to being acknowledged as just (presumably gender-neutral) scientists.

Beginning in the 1960s, the civil rights movement and the women's movement combined to subject gender inequality in science to social, cultural, and legal scrutiny. Overt discrimination became illegal. Shortages in scientific personnel in the late 1980s led to development of a gender-responsive science policy that would enable more women to become scientists and combine their professional careers with diverse family choices. Several policy initiatives by the National Science Foundation, the National Institutes of Health, and other agencies made significant headway on the problem of recruitment. Nevertheless, gender segregation continues to plague fields such as medicine, where most women congregate in pediatrics, obstetrics, and psychiatry. New fields such as biotechnology and informatics also display a consistent pattern of gender hierarchy, inequality, and de facto segregation.

In the late twentieth century, the sociocultural expectation that women are the primary family caregivers remained a major bottleneck in reaching gender parity in science. A combination of science policy and social policy has been suggested as a plausible solution. In the twenty-first century, as innovation in reproductive biology redefines the concept of the family, and as globalization eases national and cultural constraints upon formerly dominated groups such as women, science may become a vanguard of gender equality.

Pnina G. Abir-Am

X

X RAYS. When the president of the Berlin Physical Society spoke at its jubilee in 1896, he could not manage much enthusiasm about the future of its science. Later he said that, had he known about the discovery of X rays, he would instead have expressed his joy "that the second fifty years in the life of the society had begun as brilliantly as the first." His reaction was representative: from the minute Wilhelm Conrad Röntgen made known his discovery, physicists recognized it as a tonic to their senescent science. X rays challenged theory, abetted experiments, made a public sensation, and gave doctors a diagnostic tool of unprecedented power. Until the medical profession could provide itself with the necessary apparatus, people who swallowed pins or stopped buckshot appealed to physicists to locate the mischief.

X rays refused easy classification into the available categories. They did not bend in electric or magnetic fields and thus did not belong among charged particles; and since they could not be reflected or refracted, they failed the test for light. Most physicists supposed them to be a peculiar form of electromagnetic radiation. The peculiarities of X rays included behavior unbefitting a wave, however. As the English physicist William Henry Bragg stressed, an X ray could impart to an electron almost as much energy as had gone into the ray's creation. But if a wave, the ray should have spread out from its point of origin, diffusing its energy; how then could the entire original energy reassemble when a small section of the wave front encountered an electron? This difficulty appeared the stronger when in 1912 Max von Laue and his colleagues at the University of Munich, and in 1913 Bragg and his son William Lawrence Bragg, then a student at Cambridge, showed, respectively, that a crystal can both refract and reflect X rays. Röntgen's discovery thus appeared to have properties characteristic of a wave and of a particle.

At first physicists did not worry over the properties that conflicted with the wave model confirmed by the diffraction experiments. The wave model allowed investigations of crystal structure, pioneered by the Braggs. It also made possible determination of the frequencies of the characteristic X rays emitted by the elements. These rays resemble the visible line spectrum but are simpler, depending only on the atomic number, Z, and a "screening constant" σ, indicative of the place within the atom where the electron involved in the emission of a given line ends up. The study of characteristic X-ray spectra thus helped to elucidate atomic structure. In his influential theory of the constitution of atoms of 1922, Niels Bohr made systematic use of X-ray data to determine the quantum numbers of atomic electrons. The doublet structure of some X-ray lines helped Samuel Goudsmit and George Uhlenbeck to construct the concept of electron spin in 1925.

Meanwhile, the American physicist Arthur Holly Compton reopened the shelved problem of the nature of X rays by his discovery in 1922 of what was soon called the Compton effect. According to Compton, a high-frequency X ray collides with an electron as if both were billiard balls. From relativity and the quantum theory Compton assigned the X ray a frequency, ν; an energy, $h\nu$; and a momentum, $h\nu/c$. By assuming that energy and momentum are conserved in the collision, he obtained a relation between $\Delta\nu$ (the ray's loss in frequency), T (the electron's gain in momentum), and the angles between the velocities of the interacting particles.

Measurement confirmed Compton's equations and lent such support to the material conception of X rays that thereafter atomic theorists felt obliged to work both particle and wave properties into their descriptions. Louis de Broglie moderated the behavior of photons (the word Albert Einstein introduced in 1905 for hypothetical particles of high-frequency light) by coupling them to unobservable waves;

William Henry Bragg (1862–1942) and William Lawrence Bragg (1890–1971), father and son, co-inventors of the technique of X-ray interference by reflection from crystals, for which they received the Nobel Prize in Physics in 1915. This photograph dates from February 1942.

Bohr, Hendrik Kramers, and John Slater abandoned the conservation of energy in considering the relation between electron jumps and emitted light. Erwin Schrödinger followed up de Broglie's lead, and Werner Heisenberg reworked the Bohr-Kramers-Slater approach and other work of Kramers to arrive at their alternative versions of quantum physics.

The completion of the quantum theory of the electronic cloud of the atom did not end the usefulness of characteristic high-frequency radiation in studying the fundamental structure of matter. Nature produces very hard X rays in spontaneous nuclear decay. Beginning in the 1930s, physicists analyzed the energies of these "gamma rays" for data about nuclear transformations and for help in specifying nuclear energy levels. More recently, X rays from stars have given information about stellar processes.

The diagnostic uses of X rays soon gave rise to a new profession, radiology, and, when their effect on lesions and tumors was noticed, to therapeutics against skin diseases and cancers. Demand for more penetrating and more plentiful X rays prompted a rapid development of apparatus, culminating just before World War I in the high-voltage, heated-cathode Coolidge tube. The modest gains of physics from these developments rapidly multiplied after the war, in part because of wartime electrical engineering and surplus electrical equipment. Pioneers in California—at the newly established Caltech in Pasadena and at the University of California at Berkeley—pushed X-ray generators to gigantic sizes to produce radiation that could reach deep-lying tumors. Medically they achieved little, but technically they advanced substantially the art of high-power electrical engineering in the service of science. Some of the techniques and funding for these machines supported the early development of particle accelerators for nuclear physics.

The capacity of X rays to peer into previously secret places has had many applications beyond medicine. They have been used to inspect welds, test materials, fit shoes, detect dental cavities, search pyramids for mummies, etch circuits, and so on. The use of characteristic X-ray spectra to analyze the elementary makeup of even minute samples of materials became a staple in chemical assays. The optimism immediately inspired by Röntgen's discovery, and reaffirmed in the presentation to him of the first Nobel Prize in physics (1901), has been justified repeatedly in the sciences, medicine, and industry, although long exposures and inappropriate therapies have claimed martyrs among physicians and patients.

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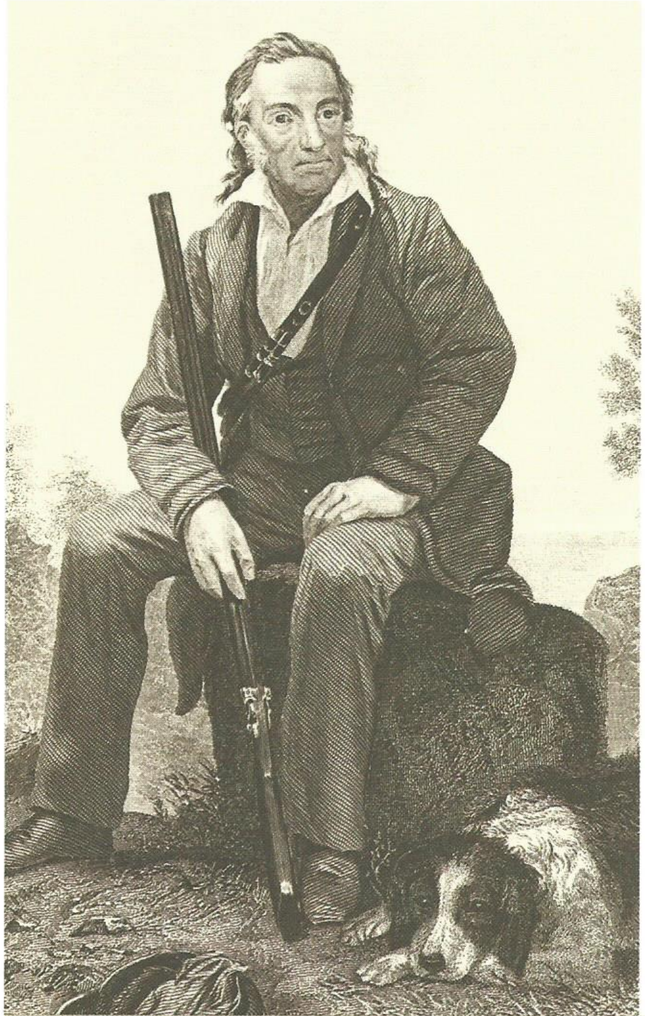
Z

ZOOLOGY. Many early modern medical treatises entitle the section or book devoted to the remedies and drugs obtained from animals "Zoology." The word's current meaning as the general science of animals emerged later, with the splitting of the old domain of natural history into several branches during the eighteenth century. Already in the sixteenth and seventeenth centuries, however, the study of animals and subfields like ornithology and entomology were the subject of independent studies by Guillaume Rondelet, William Turner, Konrad Gesner, Pierre Belon, Ulisse Aldrovandi, Thomas Moffett, John Jonston, Thomas Willis, John Ray, and Filippo Buonanni.

In 1728, the map of knowledge provided by Ephraim Chambers's *Encyclopaedia* depicted zoology as a branch of natural history, on par with meteorology, hydrology, mineralogy, and "phytology," that is, botany. The *Encyclopédie* of Denis Diderot and Jean d'Alembert (1751) placed under "zoologie" a list of subjects ranging from anatomy and medicine to hunting and falconry. The first edition of the *Encyclopaedia Britannica* (1771) devoted the entire article "Natural history" to zoology, reserving separate articles for botany and mineralogy. Its compilers adopted for the animal kingdom the system of classification provided by Carl Linnaeus, which they presented as the best and the least understood among the many systems that had been invented to introduce some order into the diversity of animal life.

In the meantime, French naturalists like René-Antoine de Réaumur, Mathurin-Jacques Brisson, and George-Louis LeClerc, Comte de Buffon, and their collaborators had devoted studies of unprecedented thoroughness and breadth to whole or parts of the animal kingdom, inspiring frequent imitation. In the second half of the eighteenth century, a growing number of authors used "zoology" in the title of books devoted to the description of the animals living in a certain region or country. From the 1770s, these local and national zoologies became a successful genre; naturalists throughout Europe and the colonies felt pressed to contribute the zoology of a region to the growing body of knowledge about animals. Similar works later became the source for the new field of biogeography.

Recognition of the independence of the study of animals came in the later 1790s with the creation at the Musée d'Histoire Naturelle in Paris of chairs devoted to specialized areas of zoological research. Jean-Baptiste de Lamarck, Georges Cuvier, and Étienne Geoffroy Saint-Hilaire were among those appointed. While adhering to diverse, often conflicting views on broad, potentially inflammatory issues such as science and religion, science and politics, evolution, and the fundamental properties of life, these naturalists and their followers in several countries shared basic notions concerning form, function, development, and classification. They also shared basic working tools offered by the cognate fields of comparative anatomy, physiology, embryology, and paleontology. During the central decades of the nineteenth century these common notions and tools—together with the widely perceived significance for culture at large of the areas of disagreement within the science of animals—helped zoologists to establish a new, powerful academic field. Among the milestones in its development were the establishment in 1848 of the *Zeitschrift für Wissenschaftliche Zoologie* by Rudolf Albert von Kölliker, the creation in 1826 of the Zoological Society that ran the London Zoo (soon imitated by similar societies elsewhere), the foundation in 1859 of the Museum of Comparative Zoology at Harvard on the initiative of Louis Agassiz, and the creation of *specialized* zoological departments within the natural history museums set up in several countries during the second half of the century. Beginning around 1860, universities throughout Europe recognized zoology as a major specialty within their natural science schools; chairs devoted to zoology multiplied in the following decades.



John James Audubon (1785–1851), French-American naturalist

Between the 1870s and the 1890s, institutional development profited from the appeal of evolutionary theories. The fame of well-known supporters of evolution like Carl Gegenbaur and Ernst Haeckel, and the renown of the teaching in German universities, attracted zoology students from other European countries and North America. The establishment of the Zoological Station in Naples (1872) on the initiative of the German Anton Dohrn, supported by Charles Darwin, and of the International Commission on Zoological Nomenclature (1895) indicated the international perspective of zoologists of the period.

Mainstream late-nineteenth-century zoology centered on morphology, the determination of phylogenetic relationships among living forms. From the 1890s, however, a new generation of zoologists trained within that same tradition launched a “revolt from morphology,” adopting an experimental rather than a descriptive approach. The protagonists of the new trend were the German zoologists Wilhelm Roux, Theodor Boveri, Hans Driesch, and Hans Spemann and the Americans Edmund Beecher Wilson and Thomas Hunt Morgan. With their work, substantial portions of zoological research moved from natural history into experimental biology, which had developed in the meantime, pursuing goals set by experimental physiology and embryology.

In the new context, which characterized much twentieth-century frontier biology, zoology and its specialties provided convenient frameworks for teaching and institutional organization rather than major subjects for research. Yet the fundamental contributions of zoologists to the evolutionary synthesis; the introduction of new fields of study like ethology, behavioral ecology, and mathematical biology; and the discovery in the 1990s of organisms in environmental niches formerly regarded as impossibly hostile have kept zoology a thriving branch of the life sciences.

Giuliano Pancaldi